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Development of Fluid Bed Gasification Control Parameters for a Range of Canadian Coals, Phase III

Final Report
by
E.G. Plett, M. Psofogiannakis
M.B. Khalil and G. Stairs

asecor ltd.

Rideau Valley Drive
Box 929
Manotick, Ontario

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ABSTRACT

The aim of the work reported herein was threefold, namely, (i) to obtain further gasification data with two lignite coals, (ii) to develop appropriate theoretical understanding of fluidized bed gasification processes to predict optimum operating conditions as well as to aid in the control of the gasifier to obtain these optimum conditions, and (iii) to develop a mini-computer based control system to allow optimum control over the gasifier to be exercised.

Some further gasification data were obtained, as presented in this report. The results are still incomplete, due to limitations in the gasifier. Some of these limitations have been improved upon in more recent work, and it is hoped that later work will clarify some of the discrepancies in results reported herein.

The theoretical model developed during this contract period is described, with results of optimization and the effect of operating away from the optimum condition shown in some detail for a well-stirred reactor. The model for a plug flow reactor is described, but detailed results for a system operating in this mode will be shown in a later report.

The mini-computer-based control system has been developed for the purpose of controlling the fluidized bed operation at a specified optimum condition. The hardware and software being used

in this system are described in this report. Final installation and testing of the system is not complete to date, but will be described in the report on the current year's work.

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The work described herein was coordinated through Asecor Ltd., with subcontracts awarded to Carleton University and Fairchild and Stairs Manufacturing (FSM) Limited. The gasifier discussed is located at Carleton University, and the computer-based control system was developed at FSM.

TABLE OF CONTENTS

	Title Page	
	Abstract	ii
	Acknowledgements	iv
	Table of Contents	v
1.0	INTRODUCTION	1
	1.1 Status at the Start of This Work	1
	1.2 Objectives of the Third Year Study	2
2.0	GASIFICATION STUDIES	3
	2.1 Operating Conditions	3
	2.2 Results and Discussion	4
3.0	THEORETICAL MODELLING	6
	3.1 Objective and Scope of the Model	6
	3.2 Kinetics of Gasification	7
	3.3 Physical Structure of the Bed	7
	3.4 Material Balances	8
	3.5 Energy Balance	9
	3.6 Algorithms for Performance Calculation	9
	3.7 Algorithms for Optimization of Performance	12
	3.8 Case Studies - Backmixed Reactor Model	13
	3.8.1 Case A: Local, low pressure syngas use	14
	3.8.2 Case B: High pressure output	15
	3.8.3 Case C: Pure O_2 and steam gasification	15
4.0	CONTROL AND DATA ACQUISITION SYSTEM DEVELOPMENT	17
	4.1 Introduction to the Control System	17
	4.1.1 Parameters Measured	17
	4.2 Hardware of the Control System	19
	4.2.1 Details of Some of the Hardware	22
	4.3 System Software	25
	4.4 FSM SC/3000 Operating Systems - Real Time Multitask FORTH	29
	4.5 Programming in FORTH	30

5.0 STATUS AT THE END OF THIS CONTRACT 34

References 35

Tables

Illustrations

Appendix A

1.0 INTRODUCTION

1.1 Status at the Start of this Work

The work reported herein is based on the third year of a study aimed at the development and utilization of a bench scale fluidized bed coal gasifier and gas burner system to be used to study the gasification behaviour of various Canadian coals. The initial development of the bench scale system is described in some detail in Ref. 1, with some modifications described in Ref. 2. Some preliminary results with the system were reported in the first two annual reports, but only limited data were obtained. Some further results were obtained during this third year, but work is continuing to obtain even more results in the fourth year work now underway.

The general dimensions and configuration of the fluidized bed gasifier as developed during the first year of this research program are shown in Fig. 1. During the second year, changes of some importance included a new coal feeder, ash pit and fly ash return as shown schematically in Fig. 2. In addition, some improvement in the method for ignition was developed during the second year.

In parallel with the gasifier development, a combustor was developed to permit studies of the combustion behaviour of low to medium heating value mixtures of gases such as obtained from a fluidized bed gasifier. Fig. 3 shows an assembly drawing of the

combustor designed for that purpose. The design was made during the second year although the fabrication was performed during later phases of this work, as will be detailed.

In summary, at the start of the third year of this program of research, the basic gasifier existed, a first generation combustor existed, and the design of a more elaborate combustor existed. Only preliminary data had been obtained with the system to the end of the second year of this study.

1.2 Objectives of the Third Year Study

There were basically three major areas of work to be pursued during this third year.

a) Gasification studies - The aim here was to obtain gasification data for two lignite coals, study the combined gasifier-combustor behaviour with these two coals and correlate the results.

b) Theoretical modelling - In anticipation of the need to be able to properly control conditions in a fluidized bed coal gasifier, an applicable theoretical description or model of what transpires in such a device was desired. The aim here was to develop an appropriate model for this purpose.

c) Control system - A mini-computer based control system was to be developed to allow the most optimum operating conditions to be arrived at for any coal under investigation in the combined process of gasification and combustion of the gas.

2.0 GASIFICATION STUDIES

2.1 Operating Conditions

As pointed out earlier in this report, the system used was described in some detail in previous reports[1,2]. In the period for which this report is written, tests were carried out using Estevan lignite of -200 mesh size, 1.69 specific gravity. The minimum fluidization velocity for these samples was computed to be 1.32 cm/s and the terminal velocity was computed to be 13.02 cm/s. A simple experimental procedure using a transparent tube was used to check the computed values. With this, the minimum fluidization velocity was observed to be about 1.5 cm/s and the terminal velocity 15.5 cm/s.

Fluidization was achieved in the bed using pure oxygen or air as the fluidizing medium. This was most easily achieved without steamflow through the distributor plate. In cases where steam was required, as for hydrogasification, it was introduced above the distributor plate, through a separate pipe.

During all the tests with the lignite coal, it was found necessary to have the ignition gases flowing in order to maintain a stable temperature in the bed. It is believed that the high heat losses from this small bed, coupled with the low heat of reaction of the lignite, cause this situation. It is an unfortunate one in that the results are contaminated by the igniter gases and their products. Better insulation may solve the problem, or a slightly larger bed may be needed. Electric trace heating is being considered as another possible solution.

2.2 Results and Discussion

Tables 1, 2 and 3 show results obtained for various operating conditions with the Estevan lignite coal. It may be noted in Table 1 that there is a high concentration of CO_2 in the product gases. In these tests, CO was used as the igniter gas, together with air, and as noted earlier, the igniter was kept on throughout the run. This will undoubtedly account for a major part of the imbalance toward CO_2. A mixture of hydrogen and helium was used as the carrier gas for the chromatographic analysis of these gases, so the sensitivity to hydrogen was poor. Therefore, rather than attributing the balance to hydrogen, it is not specified here. The nitrogen appearing in Table 1 comes about from the air used in the igniter. Using simple stoichiometric balances shows that for every mole of nitrogen coming in as a result of the igniter, 0.53 moles of CO_2 are formed in the igniter. Therefore, at least partial correction can be made for this, although the presence of the extra CO_2 affects the chemical equilibria, so that an accurate correction would require a more sophisticated analysis. It may also be noted that higher igniter flow rates were required to produce higher bed temperatures with associated higher nitrogen concentrations.

Table 2 results were obtained with similar conditions except that air is used in place of oxygen as the major fluidizing gas. This is reflected in proportionately higher nitrogen concentrations in the product gas mixture. Here again, hydrogen is not specifically shown.

Table 3 results were also obtained using air as the main fluidizing stream, but now argon is used as the carrier gas in the chromatograph, allowing some indication of hydrogen concentration to be obtained. In comparing Tables 2 and 3, the CO_2 and O_2 concentrations are in the same range, but CO concentrations are quite different, as are the nitrogen concentrations. It is hoped that further studies will help to clarify the reasons for these apparent contradictions.

3.0 THEORETICAL MODELLING

3.1 Objective and Scope of the Model

The objective of this part of the study was to develop an analytical model to permit analysis and optimization of the steady-state performance of a fluidized bed gasifier of a given design. The optimum operation of the gasifier, as well as the effects of variations in the process variables on the fluidized bed gasifier, will be predicted by the model. The model would then be applied to a given gasifier, operating with several kinds of coal and gasifying media. From these results, conclusions relating to the performance characteristics of the unit could be made and control strategies could be developed.

The immediate scope of the work was to develop two computer programs which would have the following purposes, in each case:

a) to predict the performance of a fluidized bed gasifier of given design, for the coal, gasifying media and independent process variables specified

b) to optimize the performance of a fluidized bed gasifier of a given design, for the coal and gasifying media specified.

The programs were developed to be applicable to any type of fluidizable coal and such gasifying media as O_2, air, steam, H_2, CO_2 or any mixture of the above. Details of the model and the ramifications are more fully discussed in Ref. 3. Equations as derived are shown in Appendix A.

3.2 Kinetics of Gasification

The widely adopted Johnson's model[4-6] has been adopted here. According to this model, the gasification takes place in three consecutive steps: a rapid pyrolysis step, a rapid CH_4 formation step and a slow-rate gasification step. The reactions taking place in the bed are assumed as follows:

Combustion	$C + O_2 \rightarrow CO_2$	(a)
Steam Gasification	$C + H_2O \rightleftharpoons CO + H_2$	(b)
Hydrogasification	$C + 2H_2 \rightleftharpoons CH_4$	(c)
Gas Shift Reaction	$CO + H_2O \rightleftharpoons CO_2 + H_2$	(d)
Pyrolysis	$Coal \rightarrow CO_2 + CO + CH_4 + H_2 + H_2O$	(e)

Reaction (a) is assumed to proceed until the free oxygen is consumed. The zone where this occurs is found to be a very thin zone on the top of the gas distributor. Reaction (d) is assumed to reach equilibrium. Only reactions (b) and (c) are slow enough to warrant use of kinetic relations. The detailed relations governing the gasification steps are provided in Ref. 3.

3.3 Physical Structure of the Bed

The following model of the bed structure was adopted:

a) the bed is isothermal;

b) for the particle size of the aeratable powders, the heterogeneous gasification reactions are chemically controlled; that is, mass transfer coefficients are so high that they do not impair reactions;

c) for large diameter fluidized beds ($L \leq 4D$), the bed is treated as a completely backmixed reactor;

d) for small diameter beds, ($L > 4D$), the bed is considered a plug flow reactor;

e) the solids in the bed are always completely backmixed;

f) the detailed description of the phenomena of fluidization (e.g., bubbles, emulsion phase, bubble movement, coalescence and growth, etc.) has been avoided since it is believed that with the current knowledge of the subject, such a complex model will only introduce unwarranted complications and uncertainties.

3.4 Material Balances

Mass conservation is expressed by the balance equations of the following elements: O_2, C, H_2, S and N. These balance equations are further based on the assumptions that CO, CO_2, CH_4, N_2, H_2, H_2S and H_2O are the only gaseous products of reactions, and that all O_2 fed into the gasifier reacts in the combustion zone and that 75% of the sulfur in the coal is converted to H_2S.

For the bed treated as a plug flow reactor, material balances are performed around each horizontal gasification zone; for the backmixed reactor, one material balance is performed for the whole gasifier.

3.5 Energy Balance

The energy balance accounts for the original energy content of the coal, the heats of formation as well as the sensible enthalpy of each new species formed, the heat lost through the containing walls, any auxiliary heat input as from an igniter, and the residual energy in the ash. This balance is written for the gasifier as a whole which is considered isothermal. The equation is given in Appendix A.

3.6 Algorithms for the Calculation of the Performance of a Given Fluidized Bed Gasifier

The computer program for the prediction of the performance of the fluidized bed gasifier is written in Fortran and consists of the following steps:

a) build subroutines for calculation of the enthalpies and viscosities of the gases involved;

b) read values of the constants, geometrical parameters, coal properties, various experimental variables, and the independent process variables;

c) calculate the temperature in the mixing vessel, pressure drop across the distributor and the bed, and superficial velocity at the base of the bed

d) for an assumed value of the bed density, calculate approximations for the minimum fluidization velocity and bed height;

e) on the basis of bed height to diameter (L/D), choose backmixed reactor model for $L/D \leq 4$, and the plug flow model for $L/D > 4$ as outlined next.

i) Backmixed Reactor, Case A

The major problem in computing the performance of the gasifier is the solution of the seven interrelated unknowns which include the bed temperature, T and the six syngas and bed components, C, CO, CO_2, CH_4, H_2 and H_2O. These seven unknowns may be linked by seven equations including the energy conservation equation, the elemental mass balances for O_2, C and H_2, the equilibrium of the gas shift reaction and two equations originating from the chemical kinetics (one deals with the carbon conversion ratio and the other with the amount of CH_4 formed).

After several transformations, the system reduces to five equations linking five unknowns, because of earlier assumptions made. Each of these is written in the form:

$$F_i = F_i(T, X_{II}, X_{III}, M''_{CH_4}, M''_{CO_2}) = 0$$

The solution of this system of equations is equivalent to the solution of the following optimization problem:

$$\min F = \min \left(\sum_{i=1}^{5} F_i^2 \right)$$

which is solved using the finite difference modified Levenberg-Marquardt algorithm. This algorithm is linked to the main computer program as a subroutine.

ii) Plug Flow Reactor, Case B

For this case, the bed is divided into one combustion zone and 'N' gasification zones. The gas composition is assumed to be constant within each zone but differs from zone to zone. The equations are written in the same way as for ~~the previous model for~~ the previous model for each zone, so that a system of 3N+2 equations for 3N+2 unknowns is obtained. These are solved in a way similar to the previous case.

f) When the composition and temperature of the syngas and the composition of bed solids and rejects are known, the final correct values of the following parameters are calculated:

- bed density and active height
- density, viscosity, flow rate and superficial gas velocity on top of the bed
- minimum fluidization velocity and terminal velocity.

g) At this point, a check is made to be certain that all the constraints have been satisfied and that the correct physics has been applied.

h) Finally, the performance parameters such as:

- heating value of the syngas
- sensible enthalpy of the syngas
- power output of the gasifier
- thermal efficiency of the gasifier
- power per unit volume of the gasifier

- carbon conversion ratio
- turn-down ratio

are computed.

3.7 The Algorithm for the Optimization of the Performance of a Fluidized Bed Gasifier

The second computer program developed calculates the optimum values of the independent process variables of a given fluidized bed gasifier, for given coal properties and prescribed limiting conditions. Mathematically, it consists of a general non-linear optimization problem with linear and non-linear equality and inequality constraints in which the value of the chosen objective function (the function chosen for the optimization) is minimized while keeping all constraints satisfied. The program was written in such a way as to allow any of the following to be chosen as the objective function about which to optimize:

a) maximum high thermal efficiency - considering the heating value of the syngas plus sensible enthalpy

b) maximum high/cold thermal efficiency - considering the heating value of the syngas with cold gas output so that the sensible energy is not available

c) maximum high power output - the power output corresponding to the maximum high thermal efficiency

d) maximum high/cold power output - the power output with syngas as in b) above

e) minimum high power output - minimum power output while still operating satisfactorily, with high temperature syngas output

f) minimum high/cold power output - as for e) except that the syngas output is cold or at ambient temperature

The optimum conditions corresponding to cases c) through f) are used to compute the turn-down ratio of the gasifier.

When the algorithm uses the backmixed reactor model, thirteen variables are considered as unknowns, i.e., eight independent process variables and five interrelated (as described in Section 3.6) dependent process variables. For the plug flow reactor model, the number of unknowns is increased to 3N+10, where N is the number of gasification zones into which the bed is divided. The optimization problem is solved numerically on a digital computer using the "Generalized Reduced Gradient Algorithm" (GRG), an extension of the Wolfe-algorithm to accommodate non-linear constraints.

3.8 Case Studies - Backmixed Reactor Model

The computer programs developed to date have been used for several case studies in which the performance characteristics of a representative industrial sized fluidized bed gasifier were studied. The results of these studies demonstrate the types of problems which can be solved by use of the programs, and the kinds of solutions expected. During the reporting period, solutions for only the backmixed reactor model were obtained. Table 4 gives the design parameters of the fluidized bed gasifier used in the case study, and Table 5 shows the coal properties used in these calculations.

Three cases have been considered, selected on the basis of desired use of the generated syngas.

3.8.1 Case A. Local, Low Pressure Syngas Use

The syngas will be used as fuel for a local steam power plant in this case. The minimum accepted high heating value of the syngas is its reported flammability limit of 4250 kJ/SCM. The minimum pressure at the output of the gasifier should be 105 kPa. Due to the application of the syngas, air and steam are chosen as the gasifying media. Use of pure O_2 is not justified since it will add to the capital and/or operational expenses without substantial advantage. The gasifying media are assumed to be available at a temperature of up to 850 K and a pressure of up to 1000 kPa. Figs. 4-6 show the variation of the parameters involved in the gasifier for optimum operation over a range of power output, for this case. The turndown ratio, as shown, is 7.68.

Figs. 7-19 illustrate the effect of varying individual process variables about the value required for optimum performance at a power output of 400 mW. Fig. 7 shows the effect on other variables when the temperature of the gasifying medium is varied about its optimum. Similarly, Fig. 8 illustrates the effect of steam temperature, Fig. 9 the effect of air inlet temperature, and so on. Some curves show little sensitivity to the variation in the parametric process variable plotted against, others are very sensitive to it.

Fig. 20 illustrates the effects of adding external heat to the fluidized bed gasifier, other than in the form of sensible heat of the reactants, at constant power output. On this basis, a new optimum may be defined based on the amount of heat input.

3.8.2 Case B: High Pressure Output

For this case, the gasifying media are steam and air, and the minimum accepted heating value of the syngas is 4250 kJ/SCM, as for Case A, but now the minimum accepted outlet pressure will be 800 kPa. It is assumed that the gasifying medium is available at temperatures to 850 K and pressures of up to 2000 kPa. Figs. 21-23 show the variation of parameters, corresponding to optimum performance, over a range of power output when a bituminous coal is used as fuel. The predicted turn-down ratio for this case is 6.46.

3.8.3 Case C: Pure O_2 and Steam Gasification

In this case, the optimization is performed in terms of maximizing the thermal efficiency with cold syngas emerging, i.e., treating the products as though they are cooled to ambient temperature before being used. Therefore, the power output is measured on the basis of the ambient temperature (cold) syngas energy content. Pure oxygen and steam are used as gasifying media in order to produce a syngas with a heating value of at least 8500 kJ/SCM. The minimum accepted syngas pressure is 105 kPa and the highest possible temperature and pressure of the syngas are 850 K and 1000 kPa, respectively.

The results of the optimization for this case are illustrated on Figs. 24-26, with the cold power output used as the independent variable. Operating between the maximum and minimum possible cold power output which ensures a heating value of the syngas above 8500 kJ/SCM allows a turn-down ratio of 7.10.

Figs. 27-33 show the variation of parameters, corresponding to optimum performance, over the range of power output which satisfy the minimum heating value criterion.

4.0 CONTROL AND DATA ACQUISITION SYSTEM DEVELOPMENT

4.1 Introduction to the Control System

From the complex interrelationships of variables observed in the theoretical analysis, it is apparent that it would be nice to have a control system which can aid in locating the optimum operating condition. The aim of this part of the project was to develop such a control system with a computer-based operation to allow optimum conditions to be found and maintained during operation.

The system developed was intended to provide several facilities for the operation of the coal gasifier apparatus. It is intended to provide control assistance in the setting and maintaining of a desired condition of operation up to the point of automatic control of the apparatus. It is also intended to derive and save data concerning the states of various measured stream flows and other parameters of operation.

4.1.1 Parameters Measured

Three feed gas streams, including dry steam, are instrumented and controlled. The coal feed is controlled, but not instrumented, since experience has demonstrated that a small flow of powdered solid is not easily measured. Coal feed must, therefore, be inferred from the feed rate set and from measurements of temperature, pressure and effluent gas composition. The system can utilize memory, however, in correcting the flow rate of coal, based on the change of other properties from previous changes in flow.

Effluent gas composition is measured in a semi-automatic operation at present. Gas is sampled on a schedule and fed to a gas chromatograph, the output of which is monitored by the control system. The sample and feed operation is manual, at present, but the result of the composition calculation is available for purposes of automatic control.

Measurements within the gasifier include differential pressure across the diffuser and across the fluidized bed, plus gauge pressure in the bed, as well as a series of wall temperature and a traversing probe, as described in Ref. 2.

Other methods of instrumentation may be introduced at a later date, including ultra-sonic, infrared or microwave sensing of the behaviour and height of the fluidized bed. Chemical sensors may be introduced to measure gas concentration above the fluidized bed, and various means may be employed to determine particle behaviour in the apparatus, such as perhaps, a laser doppler measurement. The above measures would require modification of the apparatus, and not all of these would be required or even desired on any one apparatus. They would also add to the cost of the apparatus, quite substantially. However, the control system is capable, in principle, of accommodating these methods, and others, for purposes of control.

In the following text, the control system architecture is discussed, with particular reference to this apparatus. The control philosophy is based on the practices of FSM Ltd., as developed

by Gavin G. Stairs, who is President of that company. Also discussed are the particulars of hardware and of the system software which is supplied to permit the system to be operated in a straightforward way, without undue concern for matters of detail.

4.2 Hardware of the Control System

The computing system hardware may be divided into two parts:

a) the display, keyboard, printer, storage and development system;

b) the analog-to-digital conversion, digital input, actuator output and control system.

The two parts are connected by a communication line for data interchange, and particularly to down-load programs and commands from the development system to the control system, and to pass state data from the control system to the development system for display and storage. After both systems have been initialized, the systems may be operated together, for logging of experimental data and display of system parameters, or separately for independent control and development or analysis.

All of the hardware necessary for control of the experiment is contained in the control system. With the addition of the independent ROM (Read Only Memory), or magnetic storage, for operating program initialization, the control system would be capable of stand-alone, turn-key operation, as in a factory setting. In this particular research and development facility, it is desirable

to have facilities for analysis and development not required otherwise. For this reason, a subsystem is supplied to suit these needs. In the present case, for reasons of economy, a TRS-80 Model I microcomputer with two 5-1/4" disc drives, an IDS-440G printer and an RS-232C serial interface for data linkage to the control system is used for this purpose. Further description of these system components may be found in literature supplied by Radio Shack and IDS.

The control system consists of an FSM SC/3000 series control computer, with subsystems supplied as required for the task at hand. The SC/3000 consists of a rack-mounted system comprising power supplies, opto-isolation driver modules, CB series analog conditioning modules and an S3 microcomputer module. The S3 module and CB analog modules are housed in a common frame which constitutes a smart analog-to-digital conversion module. It is suitable for both analog and digital controller operation and analog front-end operation in conjunction with a master computer or computer system.

In a large system, this SC/3000 system would be installed in a drip-proof or explosion-proof cabinet in the factory, with communication via fibre-optic or other link to the rest of the control system. The local system would be responsible for the control of one unit, such as the present coal gasifier, and for reporting the operation of that unit to, and executing the commands of, the control system at large.

The S3 microcomputer is itself highly modular, with extremely low-cost individual function modules for all separate functions of the unit. This permits a very simple plug-replace maintenance and repair strategy, and also permits tailoring the computer to a wide variety of requirements in an extremely small package. The S3 unit is contained in a box with overall dimensions 3"x7.5"x11". The S3 supplied for this system comprises the following units:

a) S3/CPU65 - Central Processing Unit

b) S3/TPU - IV and NURAM Top Page Unit

c) S3/RAM 4K - 2114 RAM (4K bytes)

d) S3/VMM - ROM, RAM, VRAM, EPROM (to 8K)

e) S3/BPC - Parallel I/O Port/CB Interface

f) S3/FPD - Front Panel Driver

g) S3/ADC - Analog-to-Digital Converter with switchable gain amplifier and 8-channel bipolar multiplexer - 12-bit precision

For further information on these modules, reference can be made to individual FSM datasheets.

Most analog modules consist of a mother module with semiconductor switch multiplexers, and CB/S3 bus interface; and individual signal conditioning modules which plug into the mother module, to which signal lines are connected. In this manner, up to a maximum of 32 signal lines may be connected through 8 conditioning modules. Some conditioning modules use only 1 or 2 signal positions.

Special purpose CB modules do not conform to this description. These modules may employ special isolation hardware, or special inputs, such as pressure lines for pneumatic to voltage conversion. As these modules are intended for service close to the transducers, floating inputs and current mode transmitters may often be dispensed with. This permits the greatest possible density, resulting in very compact systems.

The individual conditioning modules supplied for this system comprise the following units:

a) CB/SMSGPT - Monolithic Pressure Sensor Device

b) CB/TICT (AD590) - Temperature Integrated Circuit Transducer

c) CB/μV GSA - Micro Volt Gain Set Amplifier

These devices are supplied in the following mother modules:

a) CB/MA32 - Multipurpose Mother Module

b) CB/MA32TC - Thermocouple Isothermal Mother Module

Each of these is discussed in further detail in the following paragraphs.

4.2.1 Details of Some of the Hardware

a) CB/SMSGPT (Silicon monolithic strain gauge pressure transducer) - This module is intended to buffer National Semiconductor type monolithic devices, with an excitation voltage supplied, with redundant current limiting, and the following voltages readable:

i) excitation voltage

ii) temperature (bridge apex)

iii) bridge differential

iv) bridge offset

This module is specifically intended for use with microprocessor systems, as the compensation is left entirely to the microprocessor. This enhances reliability and self-checking capability.

b) CB/TICT (Temperature integrated circuit transducer)

- This module is intended to buffer Analog Devices AD590 type devices, with excitation voltage supplied with redundant current limiting, and current conversion. The following voltages may be read:

i) Channel 1 supply

ii) Channel 1 current (temperature)

iii) Channel 2 supply

iv) Channel 2 current (temperature)

The output is proportional to absolute temperature.

c) CB/μV GSA (Microvolt gain set amplifier)

- This is a high density minimum path amplifier for low level signals, such as thermocouples and strain gauge bridges. The common mode swing is ±10V, and the maximum signal without input attenuator is 1V. With input attenuation, signals up to several hundred volts may be accommodated. Diode clamping of the inputs

is applied after the input attenuator, on both inputs to the instrumentation amplifier. Gain may be set in decades by jumper selection on the true instrumentation amplifier. CB/μV GSA is used here to read thermocouples in a CB/MA32TC. Up to 28 thermocouples may be read. A CB/TICT is used to read the local temperature. Temperature conversion is done in software. To handle state I/O, two mother board modules are used:

i) CB/MSO512 - 512 output channels

ii) CB/MSI512 - 512 input channels

These units provide state I/O in a very dense package, suitable for use with outboard opto-isolation (e.g., OPTO-22 microprocessor systems). Conditioning modules for digital I/O may be of many types, but the fundamental types are opto-isolated output latches, and opto-isolated buffer inputs. The state of both inputs and outputs may be read by the microprocessor so that the state of output latches need not be inferred or separately stored.

In most cases, control of motors and actuators is effected by relegating logical tasks to the S3 system, and driving control lines directly through opto-isolation lines. AC line zero-crossing synchronization is performed in the opto-isolator, for noise free switching. A stepper motor is driven by driving each phase line separately. This permits the motor to be driven in either direction, or latched in position, or released. Motors may be driven in alternate or split phase. An AC motor is driven by a TRIAC AC controller directly, or a control line to an interrupter, depending

on the size of the motor. Reversing is performed by control of a separate reversing relay, to assure mutual exclusion between the directions. State inputs are simply buffered directly through to the S3 system by the multiplexer. All logical operations are performed by the S3 system.

Stepper motors are used to control gas flows. Feedback is supplied in two ways:

i) by measured gas flow

ii) by valve stem LVDT or DCDT.

An AC motor, unidirectional, is used to feed coal. The motor is controlled by a separate TRIAC control relay. Actuators for other functions, such as a sampling piston for the gas chromatograph, may be added very simply by the addition of more opto-isolation modules. State inputs are used for switch position sensing, such as to sense the gas chromatograph operator's signal to start a run.

4.3 System Software

System software may also be separated into two sections:

a) TRS-80 Model I System

b) FSM SC/3000 System.

Both systems operate with a language system called FORTH. Commands and programs may be passed from the TRS-80 to the SC/3000 via the serial line link as FORTH commands, or words.

The TRS-80 FORTH system is resident on disc. When the system is powered up with the system disc in place, the FORTH system is automatically loaded.

The FSM SC/3000 FORTH system is resident in ROM. Operation is automatically passed to FORTH on power. New program words may be added via the TRS-80 to reside in RAM space, or new EPROM or ROM may be added containing new words. By alteration of the RESTART vector switch register, operation may be initiated in an inactive monitor mode, in which the computer waits for a command before doing anything, or in an active control mode, in which the computer automatically starts to execute a previously defined control sequence.

Any system which can generate sequences of ASCII codes can be used to communicate words to the FSM SC/3000 system. Words communicated in this way are used to re-define the operation of the local system. Therefore, an SC/3000 can act as a system node in a general adaptive control system. Flexibility is extremely great. In the present system, the TRS-80 is used to control the SC/3000 in this way. This permits the system to be re-configured at will, in an extremely quick and simple way, after which the controller will operate in a fashion precisely analogous to subsequent operation as a ROM controlled dedicated controller.

The serial line is also used to pass data from the controller (FSM SC/3000) to the analyzer-logger (TRS-80). In an industrial situation, this line could be used to log operational data, on a printer or tape unit, or to link up with and pass data to a larger control network. FORTH words are the tokens which denote computer operations. A word may denote an operation of arbitrary complexity. For instance, the word "+" denotes the

operation of addition on the first two numbers on the operand stack, an extremely simple operation. However, the word "INTERPRET" denotes the operation of interpreting the stream of words coming in via the system I/O port, which is an extremely involved process. The two words may be employed in exactly analogous fashion, however.

New FORTH words are defined by stringing together old FORTH words. New words so defined may be used in precisely the same way as the words which were used to define them. In this way, the language may be extended indefinitely. This property is called extensibility. Extensibility is exploited to define words which perform all of the commonly (or uncommonly) required tasks of any particular system. Thus, if a voltage is to be read from a certain transducer, a word may be defined which sets up the conversion, converts, reads the ADC, and places the value on the stack. If this corresponds to a pressure at point 25, we can do a linear scale by the following command string:

```
:P25  P25B  P25A  P25V  * + ;
```

Now the word P25 will result in the scaled present value of pressure at point 25 being placed on the stack. In the foregoing definition, ":" inhibits the process of new word definition, while ";" (semi-colon) terminates the process. "P25" is the name of the new word, being the first word following ":". Subsequent words define operations to be performed in place of P25. Here, the operations are assumed to mean:

P25B - Place the intercept constant value on the stack

P25A - Place the slope constant value on the stack

P25V - Read the P25 voltage and place the value on the stack

* - Multiply the top two values and leave the result

\+ - Add the top two stack values and leave the result

Intuitively, the effect of "P25" is clear; the pressure at point 25 is read and returned. We now have a named construct which does what we intuitively mean when we say, "Read P25". In a similar fashion, all of the fundamental and intuitively useful operations have associated FORTH words which actually perform the actions required to realize the intuitive meaning.

In the example, we left the substituent definitions hanging. Here is how values are associated with P25A and B:

```
3625    CONSTANT P25A
243     CONSTANT P25B
:P25V   25 CHANNEL OPEN READ ADC ;
```

"P25V" is defined in terms of operations which are available on the system. "CONSTANT" is a defining word which associates the value preceding with the name following. To perform an average of several values of P25, we could define "P25AV" as follows:

```
: P25AV DUP Ø SWAP Ø DO P25V + LOOP
      SWAP / P25B SWAP P25A * + ;
```

Then, 10 P25AV would return the average of 10 consecutive readings of P25.

4.4 FSM SC/3000 Operating Systems - Real Time Multitask FORTH

The FSM SC/3000 computer is a real-time multitask controller. The system program is built on and with the FORTH programming system. FORTH consists of an emulator, or interpreter of extremely simple nature, and a structure of linked definitions, which are similar to subroutines, or lists of subroutines. By appropriately modifying the emulator, FORTH may be synchronized to the hardware on which it is running, for purposes of interrupt and multiple task processing.

Although the structures involved are extremely simple, their operation is extremely complex, being essentially recursive in nature, and therefore liable to very rapid multiplication of degree of complexity. The multitask environment is interrupt controlled. In particular, a regular interrupt is used to time-multiplex resources among tasks, and to provide for RESET trapping of loss of control or halted operation. Other devices may interrupt the system for data communication. All such systems operate by means of data buffers, and semaphore flag registers.

In order for a hardware interrupt to be directly recognized by FORTH, it must be synchronized. For this purpose, a trap vector and a FIFO queue are employed. While these methods provide extremely versatile and flexible programming opportunities, overloaded systems may thrash badly. Should a thrashing condition be apprehended, or actually be observed, it is prudent to employ more than one processor.

The hardware provides for small simple systems, employing extremely powerful techniques sparingly and with finesse. The system firmware provides a programming environment which can be as simple or as complex as may be desired; simple using high level FORTH exclusively, complex using high level FORTH and machine level. Modification or extension of the system hardware and firmware is a straightforward matter for which simple procedures are defined. Firmware definitions for the control of all standard I/O ports are provided with the I/O hardware. When a full system is purchased as a unit, the firmware to match is provided in EPROM. User extensions are eminently feasible using standard FORTH procedures.

The resources and methods described above provide a system with the following properties:

a) Modular extensibility in hardware and firmware

b) Re-definable system operation

c) Switch defined power-up vectoring

d) Facilities for soft fault and program fault recovery

e) Power-loss protection of key variables and operating system parameters

f) Multiple task capability, interrupt driven by both timers and I/O devices.

4.5 Programming in FORTH

This discussion presumes a working knowledge of FORTH and FORTH structures. Refer to FORTH tutorial for introduction level information.

Programming the system begins with algorithm definition. If the algorithm is to be taken from an existing program, then the problem is one of translation. In FORTH, extensive use is made of the parameter stack by direct manipulation; in translation from languages with implicit computation structures, it is important to mimic the behaviour of data structures in that language so as to ensure that the correct values of all data are employed at each reference. If the algorithm is to be written from scratch, then FORTH may be a convenient vehicle. In this case, define the highest level FORTH words first, using convenient task subdivisions as substituent FORTH words, whether they currently exist or not.

In each case where reference is made to a FORTH word, check for adhesion to stack protocols. When a new FORTH word is to be specified, three principal characteristics must be defined: stack input/output, variables/ports referenced, and algorithmic function. As each new FORTH word is defined, its substituents must subsequently be defined, in a process which should converge relatively rapidly onto the FORTH firmware set of definitions. When all new constructs have been completed in terms of pre-existing constructs, the definition task is complete, and implementation may proceed.

As algorithm definition proceeds from top to bottom, implementation proceeds from bottom to top. One by one, choose the FORTH definitions which make reference only to existing implemented structures, and test their operation in FORTH interpretive mode. In particular, check for proper modification of the referenced data

structures, and proper algorithm execution. Where applicable, check boundary conditions.

A likely first choice of implementation order might be:

a) Predefined data types

b) New data type specifications

c) New data types

d) Most frequently used low level definitions

e) Most seldomly used high level definitions.

The last definition is the complete task algorithm. If testing has been accomplished diligently along the way, then the program will operate correctly the first time. This does not ensure that the algorithm is correct; merely that the definitions are functional.

All definitions should be concise, occupying no more than a few lines of FORTH. Diligent effort should be devoted to producing readable FORTH code. FORTH is very dense, and is not intrinsically readable. It can be made partically unintelligible by the use of ill-advised definition names and inept task divisions.

FORTH is highly structured in normal use, providing block structured code and clear, non-interfering control structures. Programs and algorithms may be defined in terms of flow charts. FORTH is very suitable for the implementation of such charts, as their structures are very similar. When working from flow charts, it is important to keep track of stack use, and other data/I/O references, just as with direct FORTH algorithm development.

The principal programming aids in FORTH are vocabulary lists. These may be organized according to function, or ASCII/ alphabetical order or some other scheme. In any event, these vocabularies represent the available system resources. Every programmer must develop a mental overview of the vocabularies in order to program efficiently.

5.0 STATUS AT THE END OF THIS CONTRACT

Considerable work has been done and progress has been made with respect to gathering gasification data, theoretical modelling and development of the computer control system. More remains to be done in each of these areas, and these areas are being further addressed in the work following the currently reported work. It is expected that the theoretical model will produce very detailed predictions of what is to be expected in a gasifier of this type, and what should be the optimum operating condition. It is hoped that the experimental data will verify important elements of the model, and that the computer-based control system will allow the gasifier to be controlled by simple instructions, to operate at its optimum condition.

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Table 1. Results obtained in the fluidized bed gasifier using oxygen and steam with Estevan lignite coal.

Sample No.	Gas Analysis % CO_2	O_2	N_2	CO	Bal*	T_{Bed} °C	Fluidizing O_2 SCMH	Air SCMH	Coal Fed Rate kg/h	Steam Rate kg/h
1	49	-	9.9	36.8	4.3	300	0.264		0.275	0.48
2	45.6	1.3	11	41.1	1	316	0.264		0.33	0.48
3	47	1.0	10.2	41.1	0.7	346	0.198		0.33	0.36
4	63.3	-	-	23.7	13	422	0.108		0.33	0.18
3	51.7	0.4	20.6	15.3	12	675	0.198		0.22	0
4	40.7	3	27.2	2.1	27	677	0.156		0.22	0.21
6	44.5	0.2	28.2	6.3	20.8	646	0.18		0.275	0.24
7	45	0.2	9.6	43.4	1.8	619	0.228		0.165	0
8	54.2	-	12.2	24.7	9.9	765	0.198		0.165	0.3
9	56.2	-	14.8	15.3	15.7	700	0.198		0.22	0.3
10	56.7	2	13.1	-	28.2	586	0.198		0.275	0.3
11	58.3	2.5	13.1	1.6	24.5	580	0.144		0.275	0.36
13	51	0.1	8.2	39.2	1.5	400	0.198		0.33	0.48
14	36.7	0.2	24.6	21.1	17.4	645	0.264		0.33	0.3
15	49.2	0.2	13.1	35.5	2	656	0.198		0.22	0.3
16	58.3	0.2	13.5	18.9	9.1	473	0.276		0.22	0.24
17	58	0.8	14.9	4.5	21.8	587	0.144		0.22	0.24

* The carrier gas used in the chromatograph for these runs was a mixture of H_2 and H_e which gave poor sensitivity to H_2 in the analysis. The balance therefore may have substantial amounts of hydrogen in them.

Table 2. Results obtained using air and steam in the fluidized bed gasifier with Estevan lignite coal.

Sample No.	Gas Analysis % *					T_{Bed} °C	Fluidizing		Coal Rate kg/h	Steam Rate kg/h
	CO_2	O_2	N_2	CO	Bal		O_2 SCMH	Air SCMH		
11	22.3	0.9	31.1	9.5	36.2	414		0.311	0.275	0.2
12	22.7	1.1	32.9	5.3	38	543		0.481	0.165	0.2
14	24	0.5	31.1	12.1	33	480		0.481	0.22	0.2
16	22	1.1	25.6	26.3	25	470		0.481	0.22	0.2

* The carrier gas used for these results was the same mixture of H_e and H_2 as used for Table 1.

Table 3. Results obtained in the fluidized bed gasifier using air and steam with Estevan lignite coal.

Sample No.	Gas Analysis % *						T_{Bed} °C	Fluidizing		Coal Rate kg/h	Steam Rate kg/h
	CO_2	O_2	N_2	CO	H_2	CH_4		O_2 SCMH	Air SCMH		
3	21.6	5.3	53.7	-	1.1	-	383		0.566	0.22	0.12
4	21.6	5.2	56.6	-	1.7	-	450		0.566	0.22	0.12
5	24.3	-	56.6	-	2.7	-	444		0.566	0.22	0.12
6	22.3	1.3	56.5	2.9	2.7	-	392		0.283	0.22	0.12
8	23	2	53.4	2.9	2.3	-	340		0.566	0.11	0.12
9	24	2	55.4	2.9	2.7	-	513		0.566	0.22	0.12
10	24.3	1.6	52.8	3.3	4.1	-	548		0.566	0.22	0.12
13	28.4	2	52.4	3.3	3.5	-	530		0.566	0.22	0.18
17	26.4	5.5	53	1.4	3.5	0.2	492		0.425	0.22	0.18

* Argon was used as the carrier gas in obtaining the gas chromatographic analysis.

Table 4. Design parameters of the FBG used in theoretical studies of Chapter 3.

Parameter	Symbol	Unit	Value
Shape			Circular cylinder
Height	L_T	m	40
Inner diameter	D_g	m	6
Gas Distributor			Perforated flat plate
Diameter of holes	D_h	mm	7
No. of holes	N_D		120,000
Thickness of distributor	T_h	mm	50
Thickness of insulation	THICKN	mm	100
Conductivity insulation	K_{INS}	KW/m^2K	10^{-4}
Outside heat transfer coefficient	h_o	KW/mK	0.2
Cyclone average efficiency	η_{CN}		0.9

Table 5. Properties of coals used in theoretical studies of Chapter 3.

Properties	Units	Coal #1	Coal #2
Classification		Bituminous HI-VOL A	Subbituminous C
Fixed carbon	%	47.00	38.40
Volatile matter	%	32.09	25.20
Ash	%	18.30	16.70
Moisture	%	2.61	19.70
C	%	64.70	47.19
H_2	%	4.19	3.12
S	%	6.80	0.19
N_2	%	0.71	0.57
O_2	%	2.69	12.53
High heating value	kJ/kg	26320	18200
True density	kg/m^3	1200	1200
Mean particle size	μm	500	500
Particle size d_{P10}	μm	400	400
Initial sintering temperature	K	≥1600	≥1600
Coal pre-treatment temperature	K	500	500
Voidage at minimum fluidization	-	0.55	0.55
Reactivity factor f_R	-	1.5	1.5
Reactivity factor f_O	-	.9228	1.1870

NOMENCLATURE

English Letters

A	m^2	internal heat transferring area of FBG
Ar	-	Archimedes number
A_t	m^2	cross-sectional area of gas distributor
C	m/K.sec	experimental factor involved in the Yerashalmi correlation
C_p	kJ/kg°K	specific heat at constant pressure
CV_i	kJ/m^3	higher heating value of gas i
CV_{COAL}	kJ/kg	higher heating value of coal
$\overline{CV}_i$	kJ/kmole	higher heating value of gas i
D_g	m	diameter of gas distributor
D_h	m	diameter of distributor's holes
$\bar{d}_p$	m	mean diameter of coal particles
d_{P10}	m	diameter of the coal particle such that 10% of coal particles are smaller than this
E_{AUX}	kJ	auxiliary power, for definition see page A3
F_e	kg/m^3	elutriation rate of solid particles from fluid bed
f_L	-	relative reactivity of coal char for slow gasification reactions
F_{PS}	kg/m^3	maximum permissible amount of particulates in syngas
f_R	-	relative reactivity factor of coal char for the rapid methanation step
f_o	-	relative reactivity of original coal for slow gasification reactions, a coal property

g	m/sec^2	gravitational acceleration
HC	kJ/m^3	sensible heat content of the syngas
h_i	kJ/m^3	enthalpy of substance i
$\bar{h}_i$	kJ/kmole	enthalpy of substance i
h_o	kW/m^2K	outside convective heat transfer coefficient
I(X)	-	$\int \exp(\alpha x^2)(1-x)^{-2/3}dx$
k	kW/m°K	conductivity (thermal)
k_i	sec^{-1}	rate constant of reaction i
ℓ_h	m	thickness of gas distributor plate
L_f	m	height of fluidized bed during operation
L_{FB}	m	free-board height of the FBG
L_{mf}	m	height of bed at minimum fluidization
L_T	m	total internal height of FBG
m_{ash}	kg/kg-coal	ash content of coal
m_c	kg/sec	coal feed rate in FBG
M_i	kmole/kg-coal	chemical composition of coal $i=C,H_2,O_2,N_2,S,H_2O$
M'_i	kmole/kg-coal	feed rate of gasifying media $i=O_2,N_2,H_2O$
M''_i	kmole/kg-coal	chemical composition of syngas $i=CO,CO_2,CH_4,H_2O,H_2,N_2,H_2$
M''_c	kmole/kg-coal	ungasified carbon per kg of coal feed
M_{cb}	kmole/kg-coal	base carbon of coal
M_{cv}	kmole/kg-coal	volatile carbon of coal
MW_i	-	molecular weight of substance i
N_d	-	number of holes of distributor

P	kW	power output of the gasifier
p	kPa	pressure in the free board of the gasifier
p_m	kPa	pressure in the gasifying media mixing vessel
PC	kW/m^3	power concentration of the FBG
q_L	kJ/kg-coal	heat losses from FBG per kg of coal feed
Q_{INPUT}	kJ/kg-coal	indirect heat added to the FBG
Re	-	Reynolds number
R_u	kJ/kmole°K	universal gas constant
T	°K	temperature of gasification zone of the bed
T_a	K	temperature of O_2/air as entering the mixing vessel
T_e	K	temperature of the environment
T_g	K	temperature of syngas at the exit of the gasifier
T_m	K	temperature in the mixing vessel
T_o	K	reference temperature (298°K)
T_p	K	coal pre-treatment temperature
T_s	K	initial sintering temperature of coal
T_w	K	temperature of steam as entering the mixing vessel
t_R	sec	mean residence time of coal in the fluid bed
TDH	m	transport disengaging height
TDR	-	turn-down ratio of FBG
U	kW/m^2K	overall heat transfer coefficient, see Eqn. B5

u_o	m/sec	superficial gas velocity
u_{mf}	m/sec	superficial gas velocity at minimum fluidization
u_{pf}	m/sec	minimum superficial velocity for steady bubbling fluidization
u_s	m/sec	minimum superficial velocity to avoid sintering of bed
u_T	m/sec	terminal velocity of solid particles
V_{SG}	m^3/sec	flow rate of syngas, evaluated at the gasifier exit conditions
V_i	m^3	volume of gas i
W	kg	mass of solids in bed
X	-	base carbon conversion ratio
y	-	mass fraction of carbon in coal, on a m.a.f. basis
y_H	-	mass percentage of hydrogen in coal char

Greek Letters

α	-	kinetic parameter of Johnson's model
γ	-	C_p/C_v
$(\Delta H_f)_i$	kJ/kmole	heat of formation of substance i
ΔP_b	kPa	pressure drop across the bed
ΔP_d	kPa	pressure drop across the gas distributor
Δt_{INS}	m	thickness of insulation around the gasifier
ϵ_{mf}	-	bed voidage at minimum fluidization
η_c	-	carbon conversion ratio

η_{CN}	-	cyclone(s) efficiency
η_{TH}	-	thermal efficiency of the FBG
λ	-	expansion ratio of the fluidized bed
μ	kg/m.sec	dynamic velocity
ρ	kg/m^3	density
τ	sec	time
ϕ_s	-	sphericity of coal particles
ψ_i	-	molar/volume composition of syngas

Subscripts

a	initial condition; air/O_2
AUX	auxiliary
b	fluidized bed
c	carbon
cb	base carbon
cv	volatile carbon
d	gas distributor
e	environment
f	at steady bubbling fluidization
fg	latent
g	gasifier
H	high
HCOLD	high-cold
II	at the end of the rapid gasification steps

IIC	at the end of the rapid gasification and combustion steps
III	at the end of the slow gasification step
INPUT	indirect heat input
INS	insulation
L	low
LCOLD	low-cold
mf	at minimum fluidization
o	at reference state (298°K, 101.33kPa)
pf	at minimum stable bubbling fluidization
s	bed solids
SATUR	saturation
SG	syngas
T	total

Superscripts

-	average; evaluated on a kmole basis
o	same as subscript o
E	equilibrium

APPENDIX A

ANALYTICAL RELATIONS USED IN THE MODEL FOR THE PERFORMANCE STUDY OF THE FLUIDIZED BED GASIFIER

A. Performance Parameters

A1. $$\psi_i = M''_i \Big/ \sum_i M''_i \qquad , i = CO,\ CO_2,\ CH_4,\ H_2,\ N_2,\ H_2O,\ H_2S$$

A2. $$CV_H = \frac{P}{R_u T} \sum_i \psi_i \overline{CV}_i \quad , i = CO,\ CH_4,\ H_2$$

A3. $$CV^\circ_H = \frac{101.33}{298.R_u} \sum_i \psi_i \overline{CV}_i, \quad i = CO,\ CH_4,\ H_2$$

A4. $$CV_L = CV_H - (\psi_{H_2} + 2\psi_{CH_4}) \frac{P}{R_u T} \overline{h}_{fg}$$

A5. $$CV^\circ_L = CV^\circ_H - (\psi_{H_2} + 2\psi_{CH_4}) \frac{101.33}{298.R_u} \overline{h}_{fg}$$

A6. $$HC = \frac{P}{R_u T} \sum_{i=1}^{7} \psi_i (\overline{h} - \overline{h}_o)_i$$

A7. $$P_H = V_{SG}(CV_H + HC)$$

A8. $$P_{HCOLD} = V_{SG} CV_H$$

A9. $$P_L = V_{SG}(CV_L + HC)$$

A10. $P_{LCOLD} = V_{SG} CV_L$

A11. $\eta_c = (M_c - M_c'')/M_c$

A12. $$\eta_{TH_i} = P_i / \left[m_c \{ CV_{COAL} + E_{AUX} + \frac{Q_{INPUT}}{n_{INPUT}} + M'_{O_2} (\bar{h}_a - \bar{h}_o)_{O_2} + M'_{N_2} (\bar{h}_a - \bar{h}_o)_{N_2} + M'_{H_2O} (\bar{h}_a - \bar{h}_o)_{H_2O} / n_{BOILER} \} \right]$$

where i = H, HCOLD, L, LCOLD

B. Various Process Variables and Other Parameters

B.1 $\Delta P_b = W.9/A_t$

B.2 $\Delta P_d = \frac{1}{2} p_g u_o^2 F$

B.3 For cylindrical holes:

$$F = \frac{D_q^4}{N_D^2 D_H^4} \{ 0.016 \frac{\ell_H}{D_H} + (1 - \frac{N_D D_H^2}{D_g^2})^2 + (0.5 - \frac{0.4 N_D D_H^2}{D_g^2}) \}$$

B4. $q_L = U.A.(T - T_e)/\dot{m}_c$

B5. $$U = \left[\frac{1}{h_o} + \frac{\Delta t_{INS}}{k_{INS}} \right]^{-1}$$

B6. $E_{AUX} = 81000\ M'_{O_2\ (pure)}$, for pure O_2 generation

$$E_{AUX} = \frac{P_o \gamma_i}{.35\eta_c}\left\{\left(\frac{P_m}{P_o}\right)^{\frac{\gamma_i - 1}{\gamma_i}} - 1\right\}^{\frac{\gamma_i}{\gamma_i - 1}}$$, for pressurization of gasifying medium i

B7. $L_{mf} = W/\left[A_t \rho_s (1-\varepsilon_{mf})\right]$

B8. $L_f = W/\left[A_t \rho_s (1-\varepsilon_{mf})\right]$

where $\lambda = 1 + 13(u_o - u_{mf})^{.738} d_p^{-1.006} \rho_s^{.376} u_{mf}^{-.937} \rho_g^{-.126}$,

for $D_g \geq .0635m$

and

$\lambda = 1 + 1.0315(u_o - u_{mf})^{.57} \rho_s^{-.166} u_{mf}^{-.063} D_g^{-.445}$,

for $D_g < .0635m$

B9. $\rho_s = (X_c + X_{ASH})/\left[X_c/\rho_c + X_{ASH}/\rho_{ASH}\right]$

where

$\rho_c = 1000/(.4397 + .1223y_H - .01715y_H^2 + .001077y_H^3)$

$X_c \simeq 12(1-X_{III})M_{cb}/\left[12(1-X_{III})M_{cb} + m_{ASH}\right]$

and

$X_{ASH} \simeq 1 - X_c$

B10. $t_R = X_{ASH} \cdot W/M_{ASH}\dot{m}_c$

B11. $$u_{mf} = \frac{\mu}{\rho_g d_p}\left[((25.25)^2+.0651A_r)^{0.5}-25.25\right]$$

where

$$Ar = g\bar{d}_p^3\rho_g(\rho_s-\rho_g)/\mu^2$$

B12. For terminal particles velocity:

$$Re_T = Ar_T/18 \qquad \text{for } Ar_T \leq 3.6$$

$$Ar_T = 18Re_T + 2.7Re_T^{1.687} \qquad \text{for } 3.6 \leq Ar_T \leq 10^5$$

$$Re_T = (3Ar_T)^{.5} \qquad \text{for } Ar_T > 10^5$$

where

$$Re_T = u_T\bar{d}_p\rho_g/\mu$$

B13. $$u_{pf} = 2u_{mf}$$

B14. $$Fe = 34000\rho_g(u_o^2/d_p\rho_s^2)^{1.62}, \text{ kg/m}^3$$

C. <u>Energy Balance Equation</u>

C1. $$CV_{COAL} + M_c(\Delta H^\circ_f)_{CO_2} + M_s(\Delta H^\circ_f)_{SO_2} + (M_{H_2}+M_{H_2O})\left[(\Delta H^\circ_f)_{H_2O_g}\right.$$

$$\left. - \bar{h}^\circ_{fg}\right] + M'_{O_2}(\bar{h}_a-\bar{h}_o)_{O_2} + M'_{N_2}(\bar{h}_a-\bar{h}_o)_{N_2} + M'_{H_2O}\left[(\Delta\bar{H}_f)\right.$$

$$\left. + \bar{h}_a-\bar{h}_o\right]_{H_2O_g} + Q_{INPUT} = q_L + m_{ASH}(h_g-h_o)_{ASH}$$

$$+ \sum_{i=1}^{8} M''_i(\Delta\bar{H}^\circ_f+\bar{h}_g-\bar{h}_o)_i \text{ , } i = C, CO, CO_2, CH_4, H_2, N_2, H_2O, H_2S$$

D. Global Mass Balance Equation

D1. Oxygen balance:

$$M_{O_2} + M'_{O_2} + \frac{1}{2}(M'_{H_2O} + M_{H_2O}) = M''_{CO_2} + \frac{1}{2}(M''_{CO} + M''_{H_2O})$$

D2. Carbon balance:

$$M_c = M''_C + M''_{CO} + M''_{CO_2} + M''_{CH_4}$$

D3. Hydrogen balance:

$$M_{H_2} + M_{H_2O} + M'_{H_2O} = M''_{H_2} + M''_{H_2O} + M''_{H_2S} + 2M''_{CH_4}$$

D4. Nitrogen balance:

$$M_{N_2} + M'_{N_2} = M''_{N_2}$$

D5. Sulfur balance:

$$M''_{H_2S} = 3/4\ M_S$$

E. Relations on Chemistry of Gasification

E1. CH_4-formation during pyrolysis step:

$$M^I_{CH_4} = (0.1 + .015 p_{H_2}) . M_C$$

E2. Base carbon conversion at the end of the rapid methanation step:

$$I(X_{II}) = \int_{X=0}^{X=X_{II}} \exp(\alpha X^2)(1-x)^{-2/3}dx = .0092\ f_R\ P_{H_2}$$

where:

$$\alpha = 52.7P_{H_2}(1+54.3P_{H_2})^{-1} + .521P_{H_2}^{1/2}P_{H_2O}(1+.707P_{H_2O} + .5P_{H_2}^{1/2}P_{H_2O})^{-1}$$

E3. Base carbon conversion at the beginning of the slow gasification reactions:

$$X_{IIC} = X_{II} + M'_{O_2}/M_{cb}$$

E4. Final base carbon conversion:

$$\int_{X_{IIC}}^{X_{III}} \exp(\alpha X^2)(1-x)^{-2/3}dx = f_L k_T \tau$$

where:

$$k_T = k_I + k_{II} + k_{III}$$

$$k_I = \frac{1}{60}\left(1 - \frac{P_{CO}P_{H_2}}{P_{H_2O}K_I^E}\right)(1+\exp(-22.216+24881/T)(P_{H_2O}^{-1}+16.35P_{H_2}P_{H_2O}^{-1} + 43.5P_{CO}P_{H_2O}^{-1}))^{-2}\exp(9.0201-17613/T)$$

$$k_{II} = \frac{1}{60} P_{H_2}^2 \left(1 - \frac{P_{CH_4}}{P_{H_2}^2 k_{II}^E}\right)\left(1+P_{H_2}\exp(-10.452+11097/T)\right)^{-1}$$

$$\exp(2.6741-18375/T)$$

$$k_{III} = \frac{1}{60} P_{H_2}^{1/2} P_{H_2O} \left(1 - \frac{P_{CH_4} P_{CO}}{P_{H_2} P_{H_2O} k_{III}^E}\right) [1+\exp(-6.6696+8443/T)$$

$$.(P_{H_2}^{1/2}+.85P_{CO}+18.62P_{CH_4}P_{H_2}^{-1})]^{-2} \exp(12.4463-24746/T)$$

$$k_I^E = 10^{(7.49-7070/T)}$$

$$k_{II}^E = 10^{(-5.373+4723/T)}$$

$$k_{III}^E = k_f^E k_{II}^E$$

$$f_L = f_o \exp(4704/T) \quad \text{for } T_p \leq T$$

$$f_L = f_o \exp(4704/T_p) \quad \text{for } T_p > T$$

$$f_o = 6.2y(1-y)$$

E5. Total CH_4 production:

$$M''_{CH_4} = (.1+.015P_{H_2})M_C + X_{II}M_{cb} + (X_{III}-X_{IIC})M_{cb}\frac{k_{CH_4}}{k_T}$$

where:

$$k_{CH_4} = k_{II} + k_{III}/2$$

E6. Equilibrium of gas-shift reaction:

$$k_E = \frac{y_{CO_2} y_{H_2}}{y_{CO} y_{H_2O}} = \exp[-13.2898+5287.61/T+1.1021\ell n(1.8T)]$$

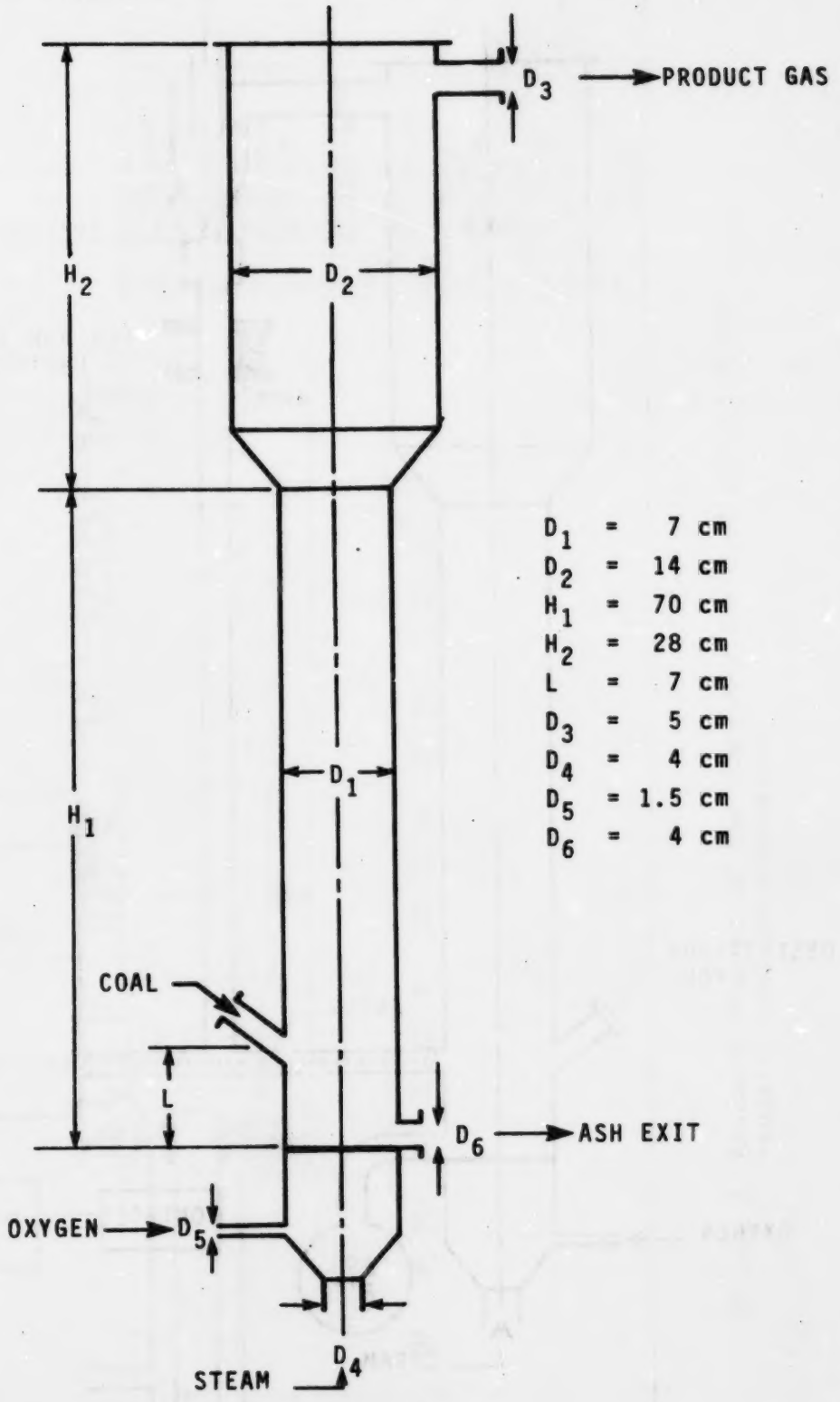

Figure 1: General Dimensions of the Fluidized Bed Gasifier as First Built

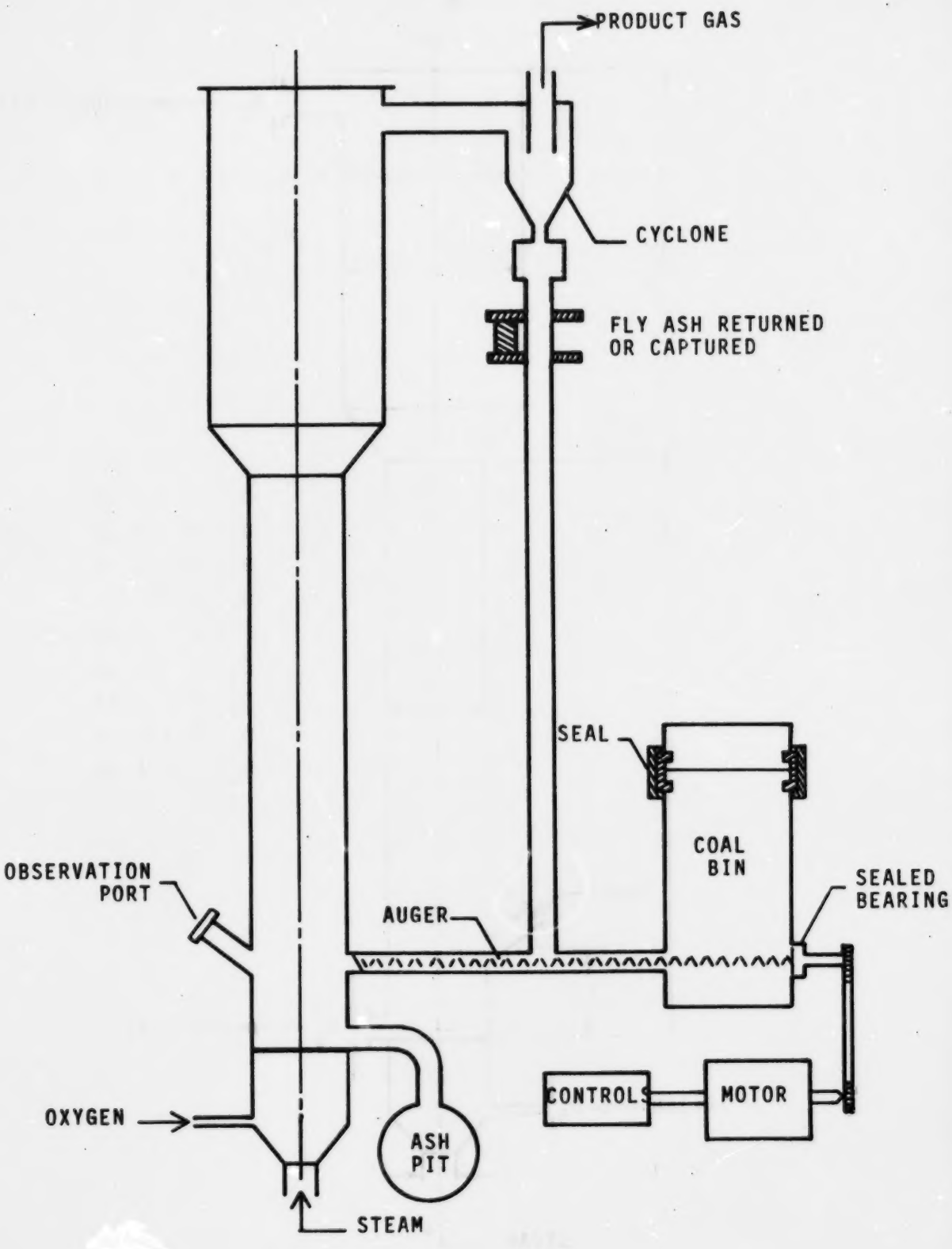

Figure 2 Gasifier showing coal feeder and ash pit which were added during the previous contract period

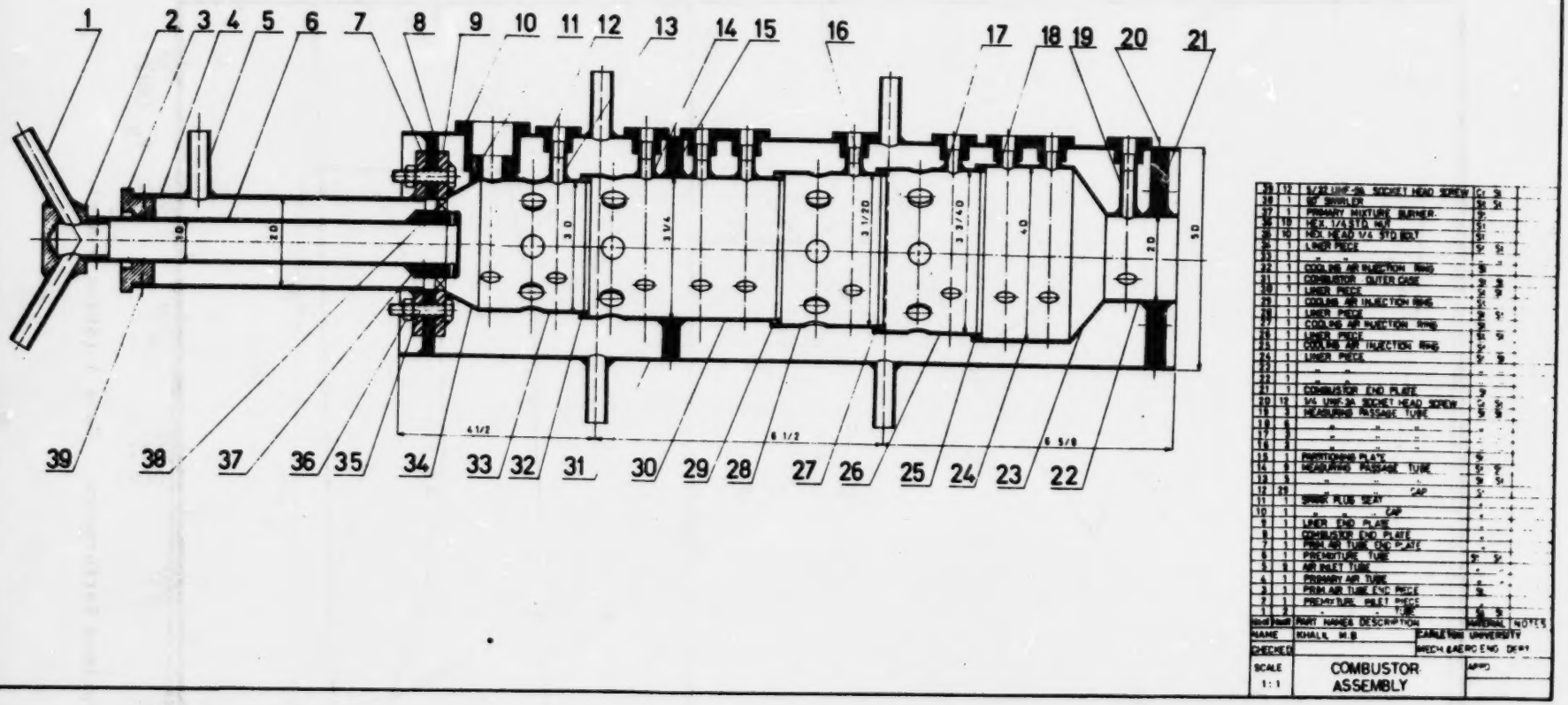

Figure 3 Assembly drawing of the combustor designed and built for studying coal gas combustion

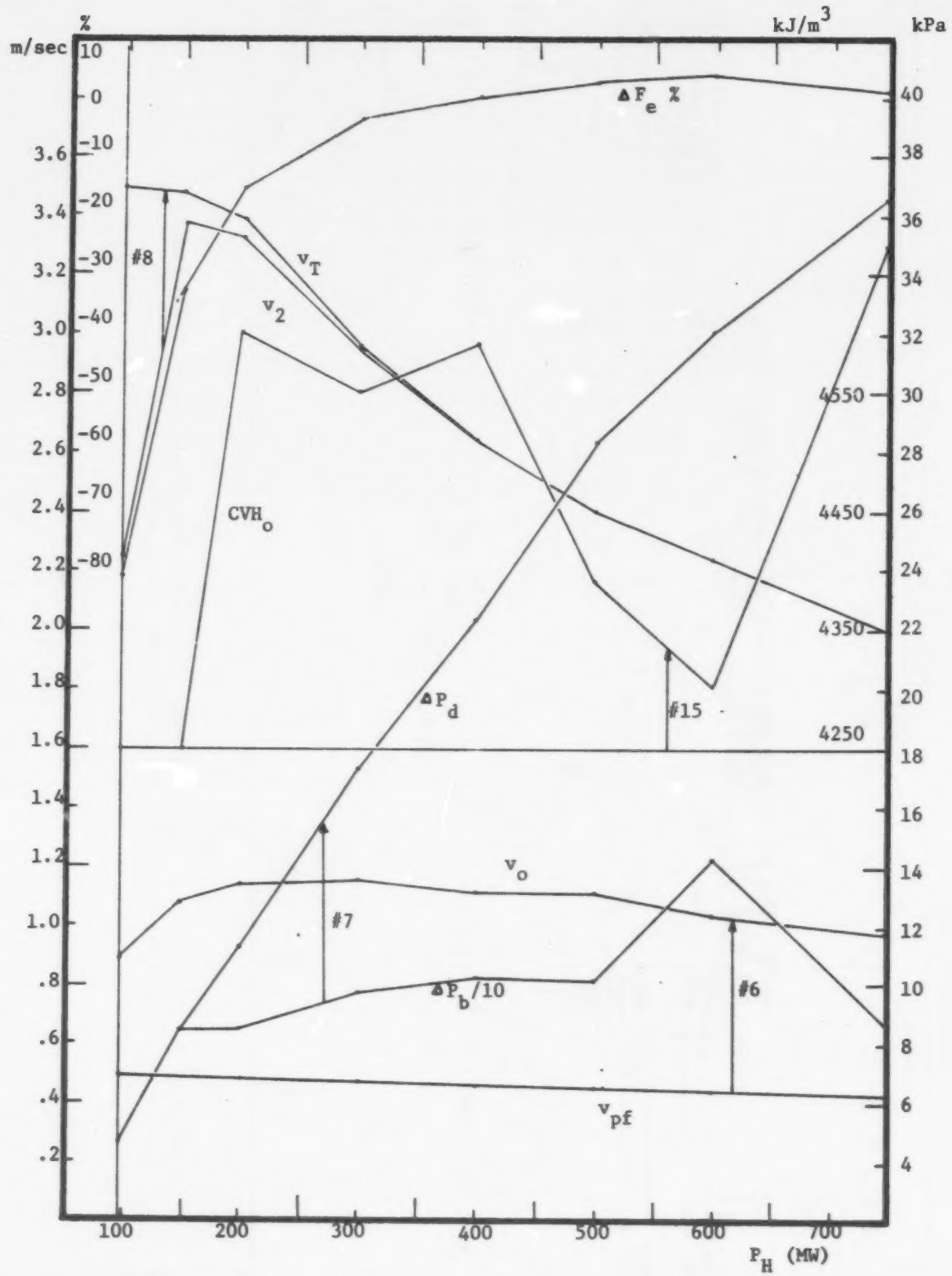

Fig. 4. Optimum Performance. Case A (Steam + Air).

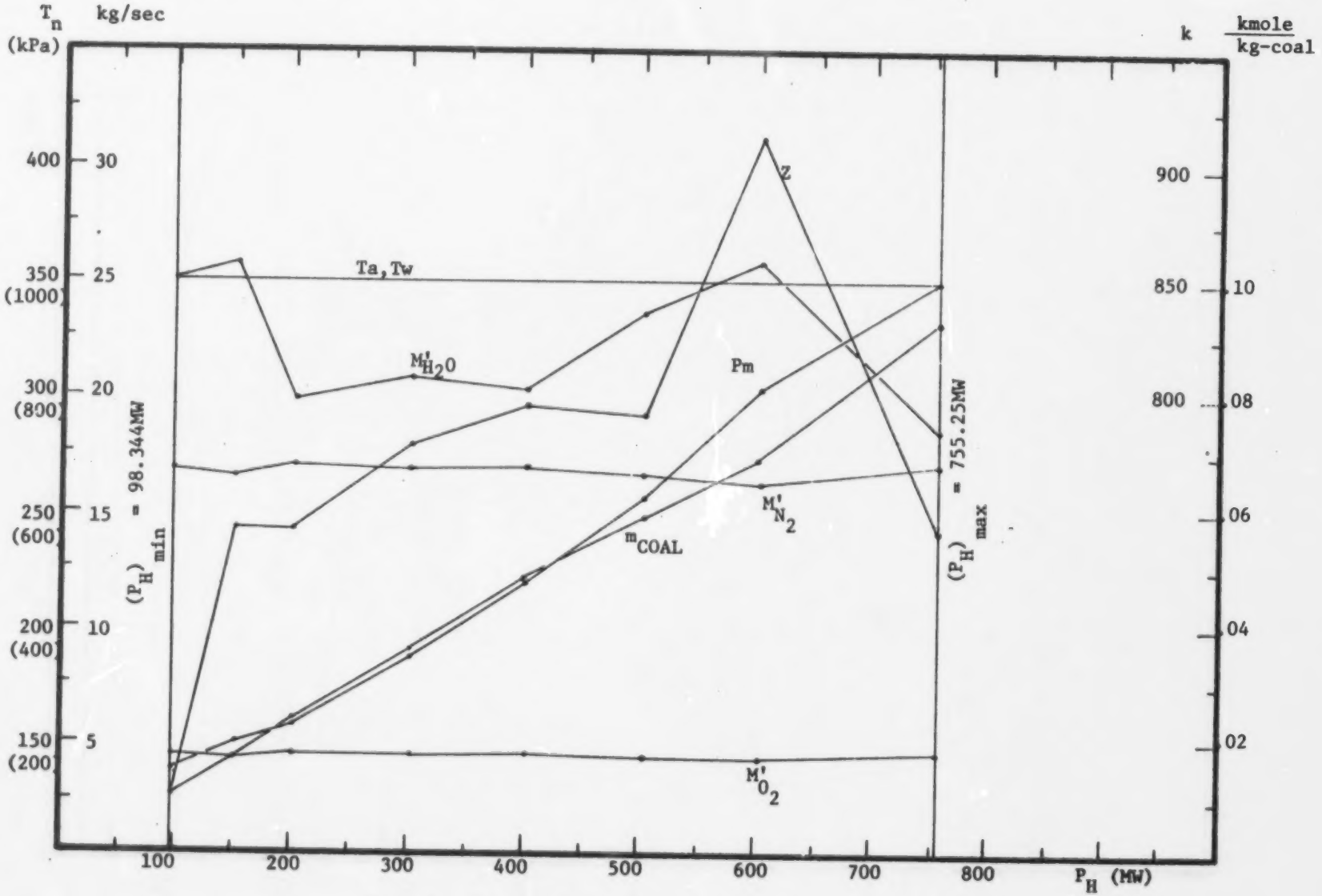

Fig. 5. Optimum Performance. Case A.

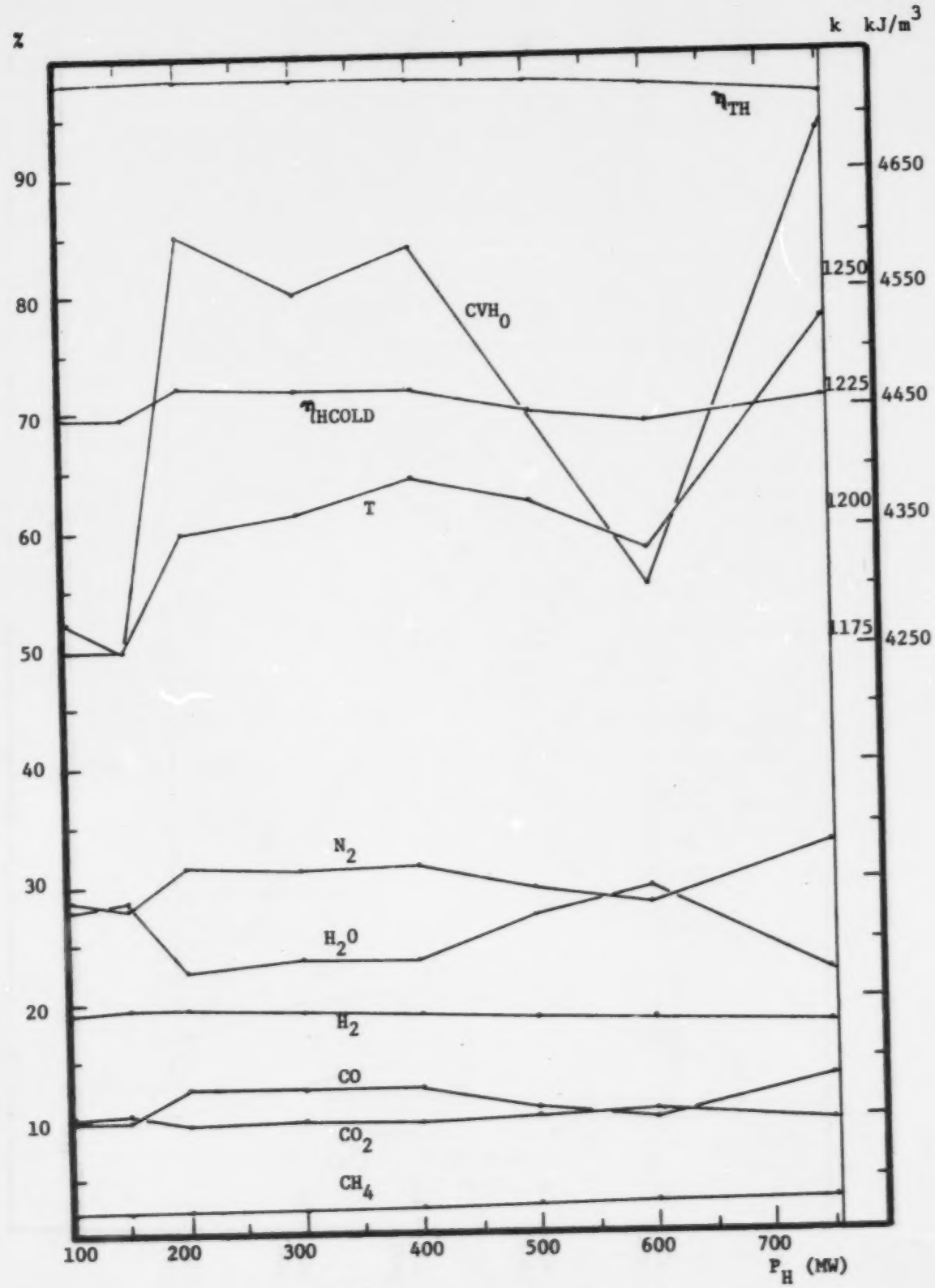

Fig. 6. Optimum Performance. Case A.

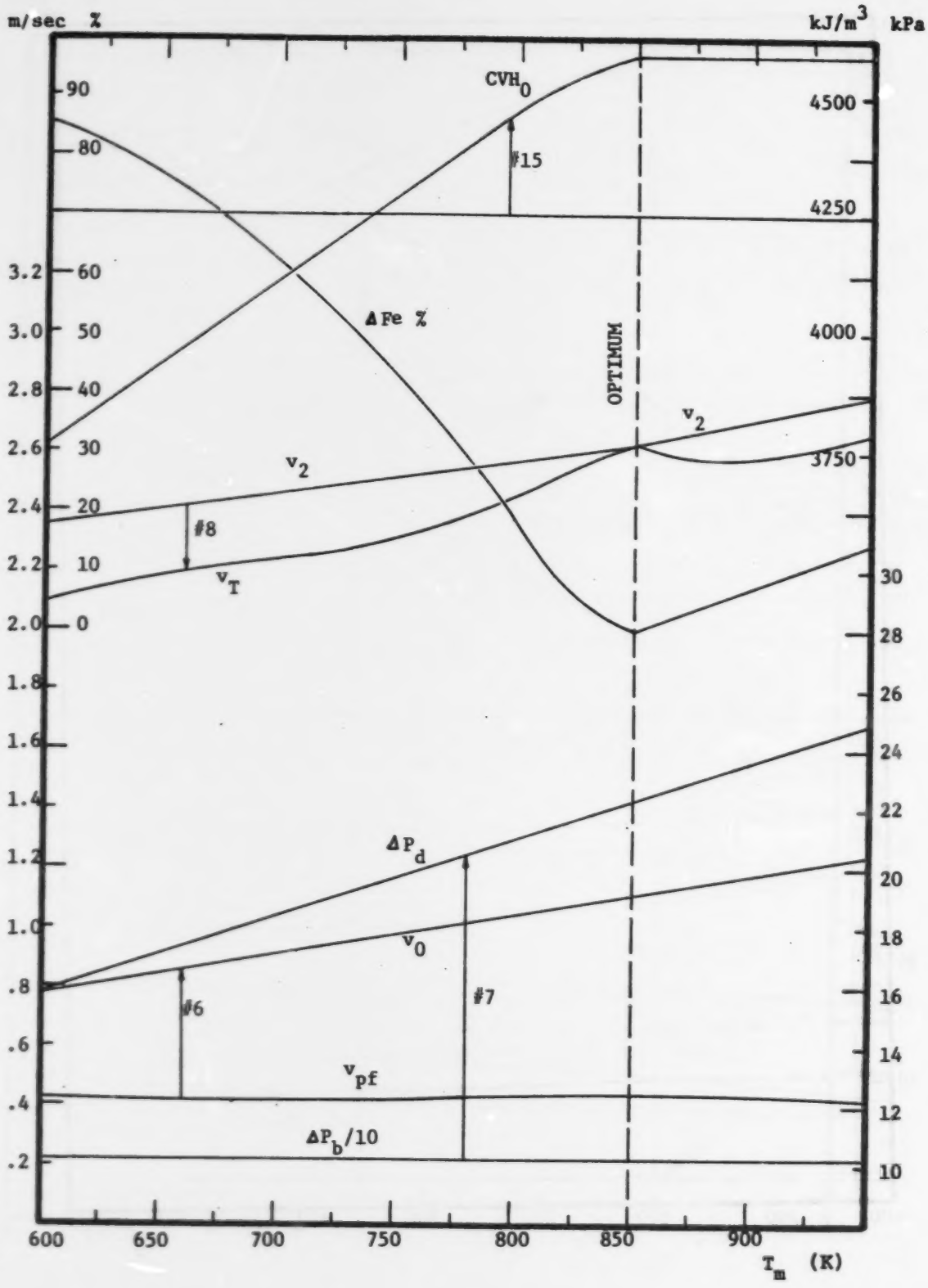

Fig. 7. Effects of variation in temperature of gasifying media on the performance of the FBG. Case A.

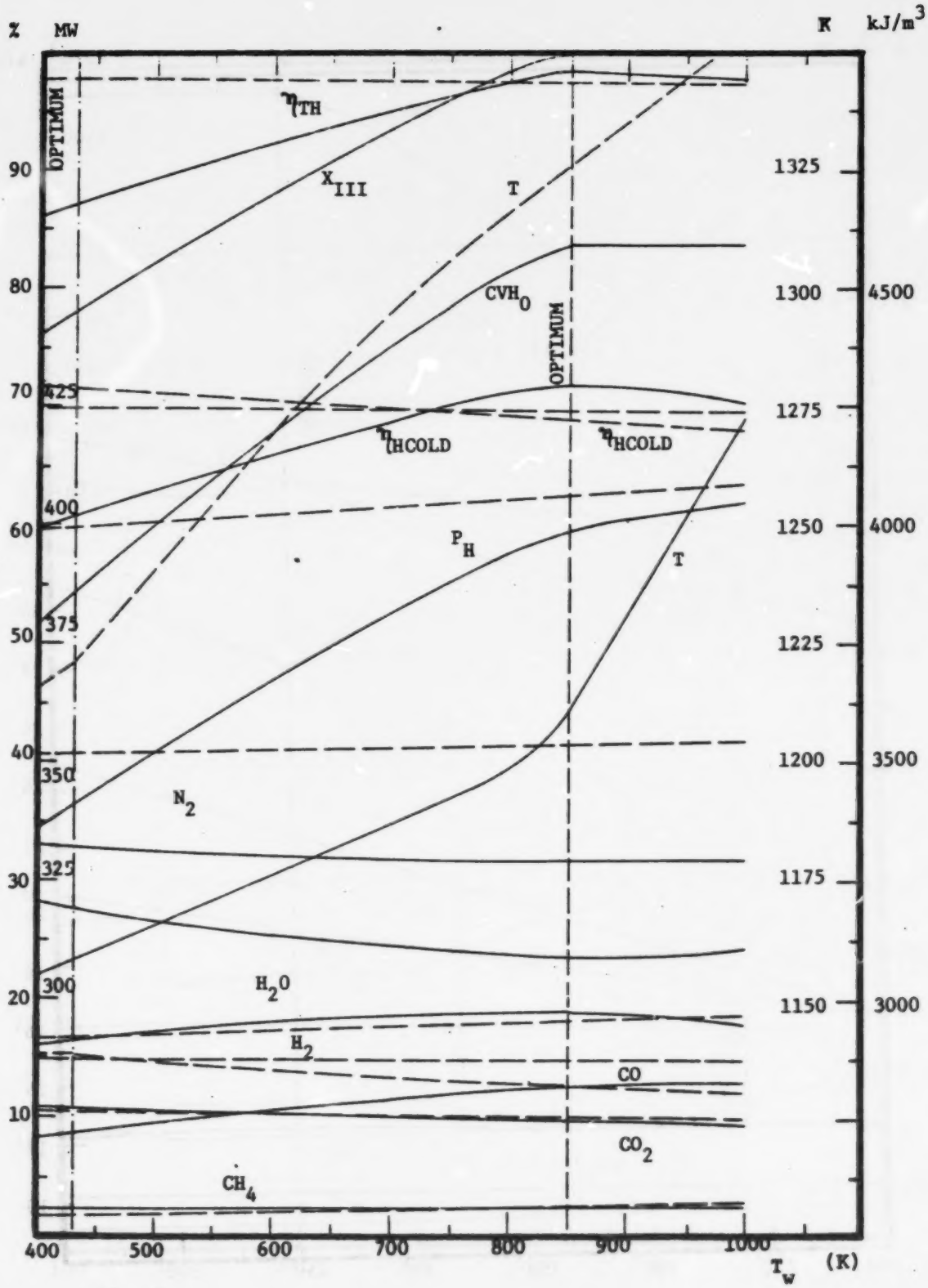

Fig. 8. Effects of variation in steam temperature on the performance of the FBG. Case A.

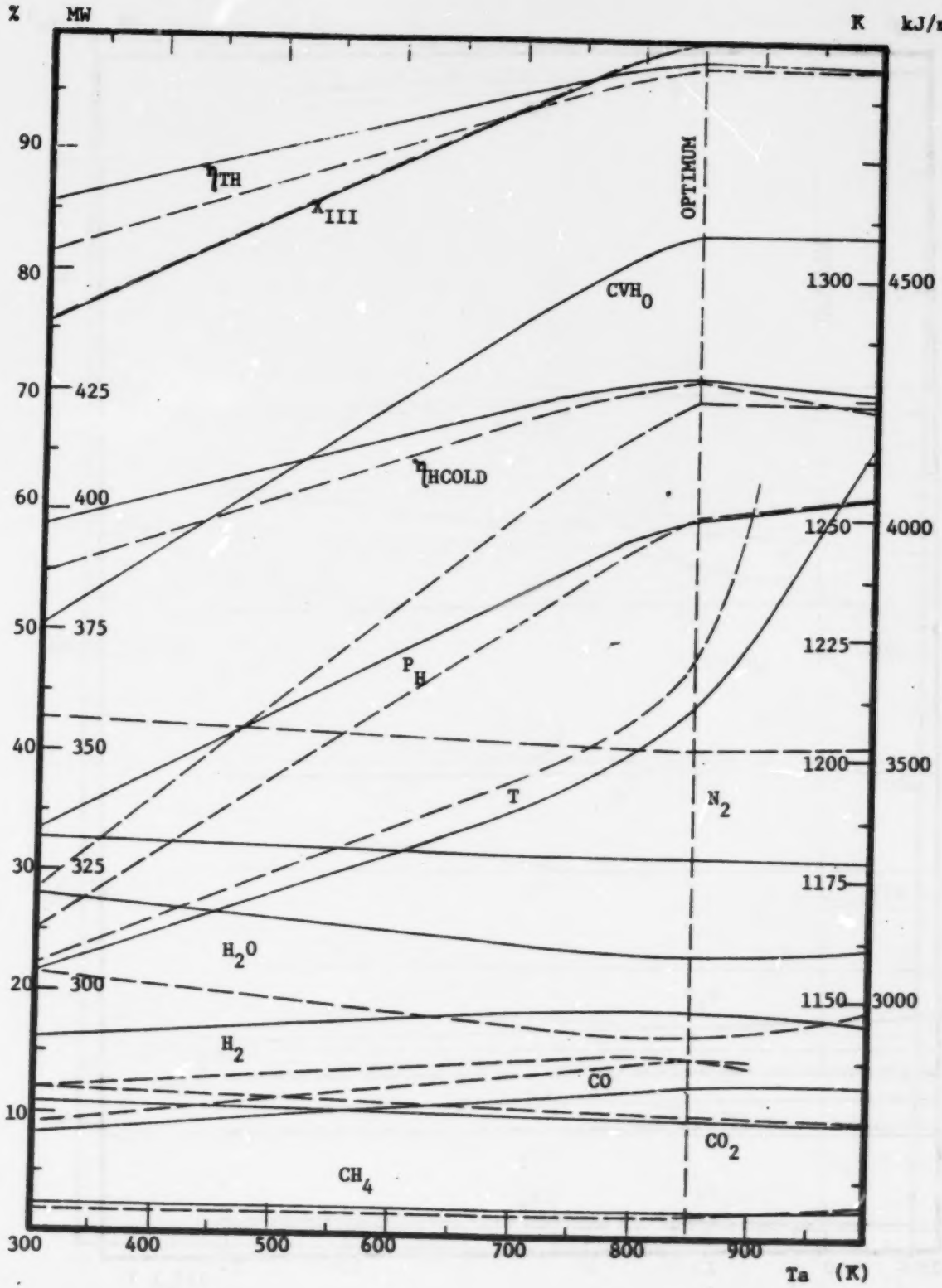

Fig. 9. Effects of variation in air temperature on the performance of the FBG. Case A.

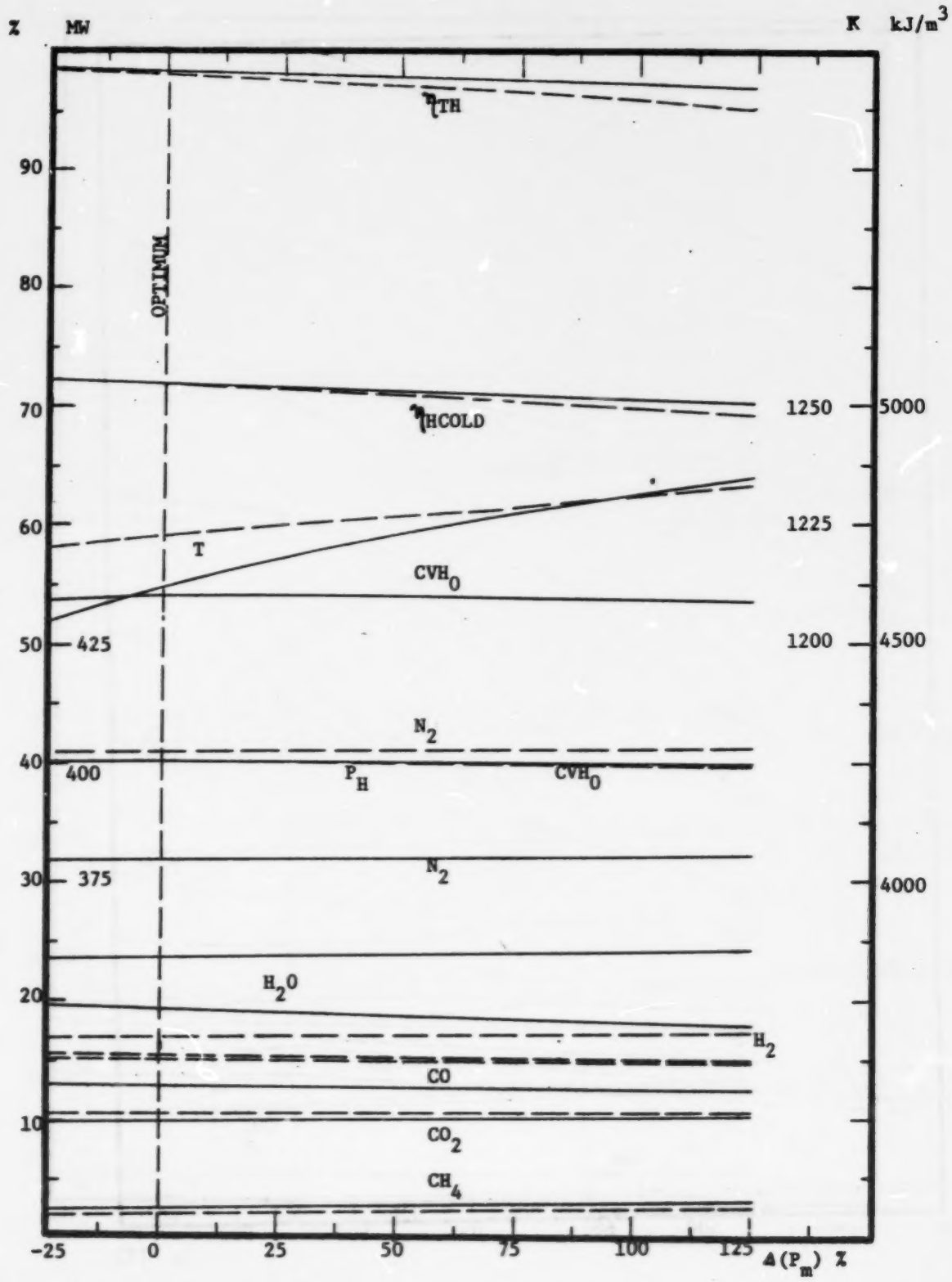

Fig. 10. Effects of variation in pressure in mixing vessel on the performance of the [illegible]G. Case A.

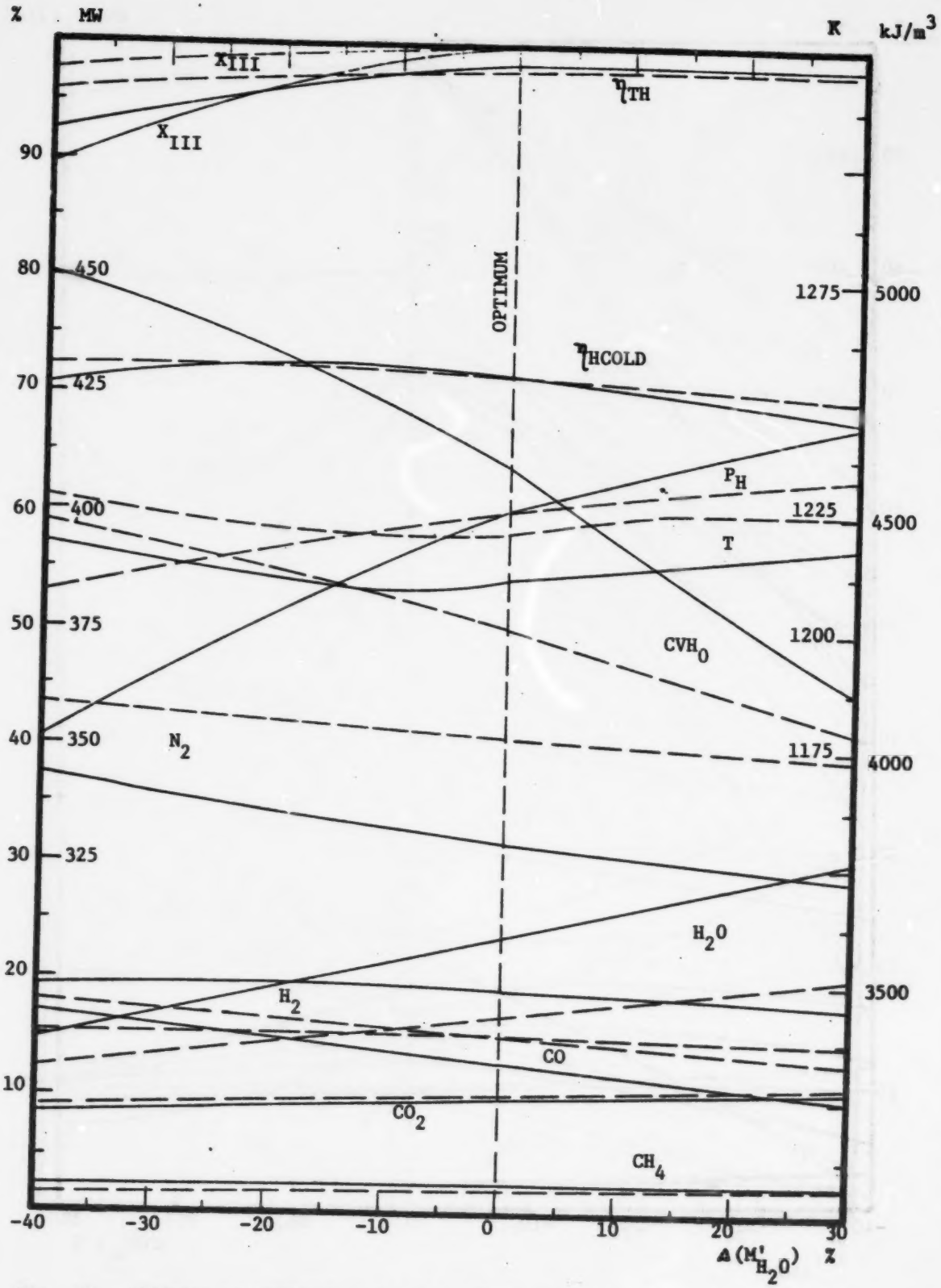

Fig. 11. Effects of variation in steam feed rate on the performance of the FBG. Case A.

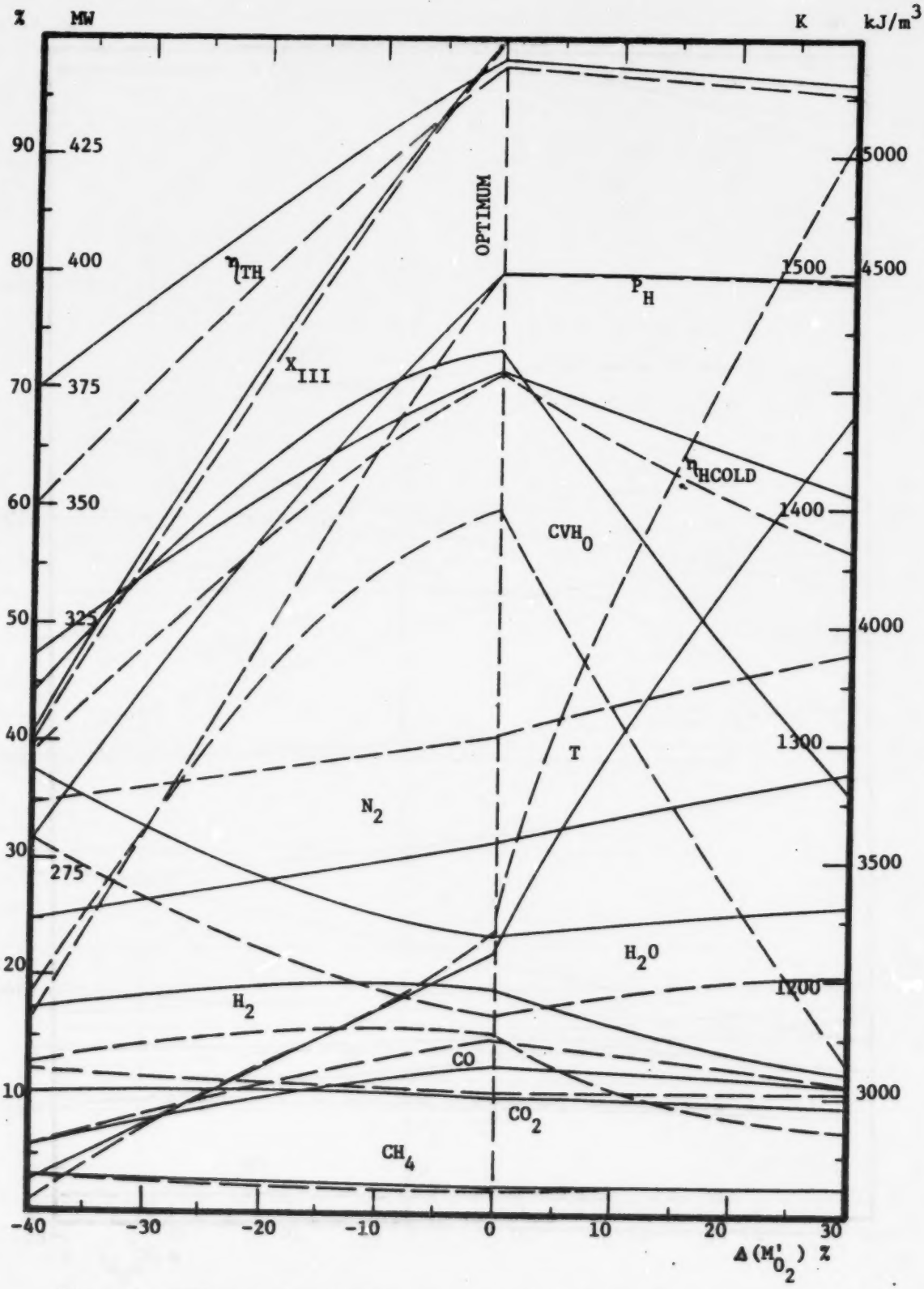

Fig. 12. Effects of variation in air feed rate on the performance of the FBG. Case A.

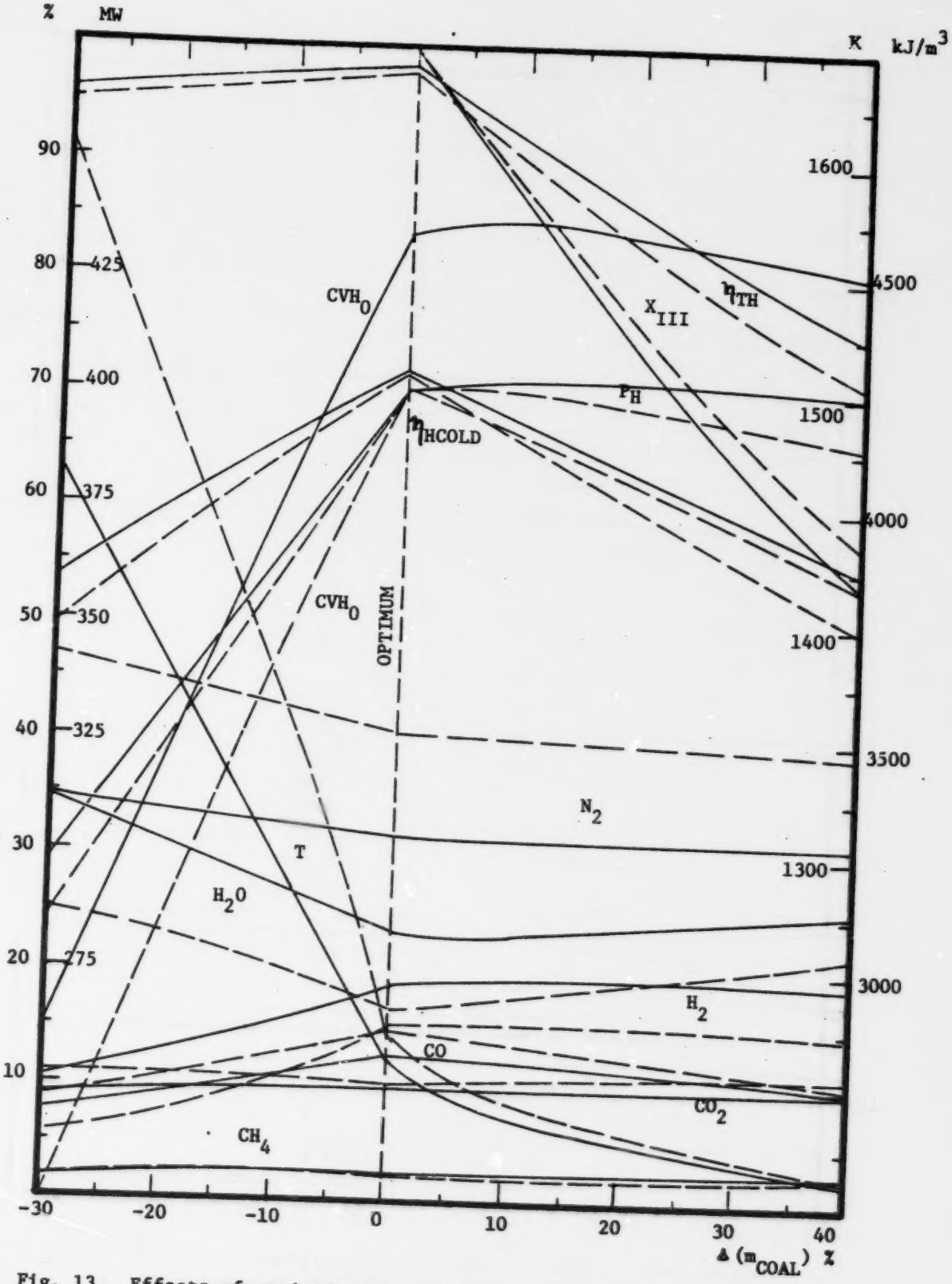

Fig. 13. Effects of variation in coal feed rate on the performance of the FBG. Case A.

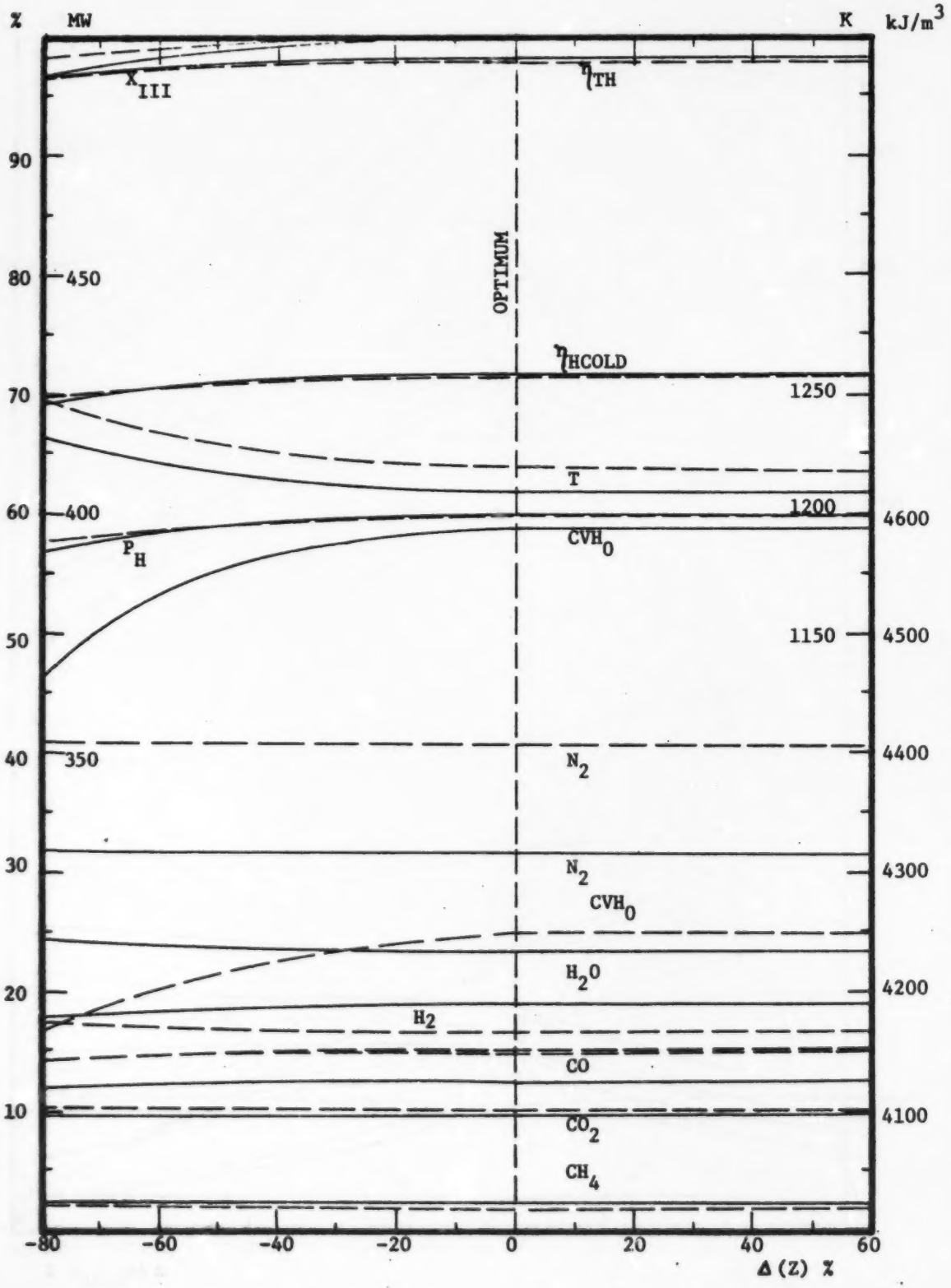

Fig. 14. Effects of variation in bed weight on the performance of the FBG. Case A.

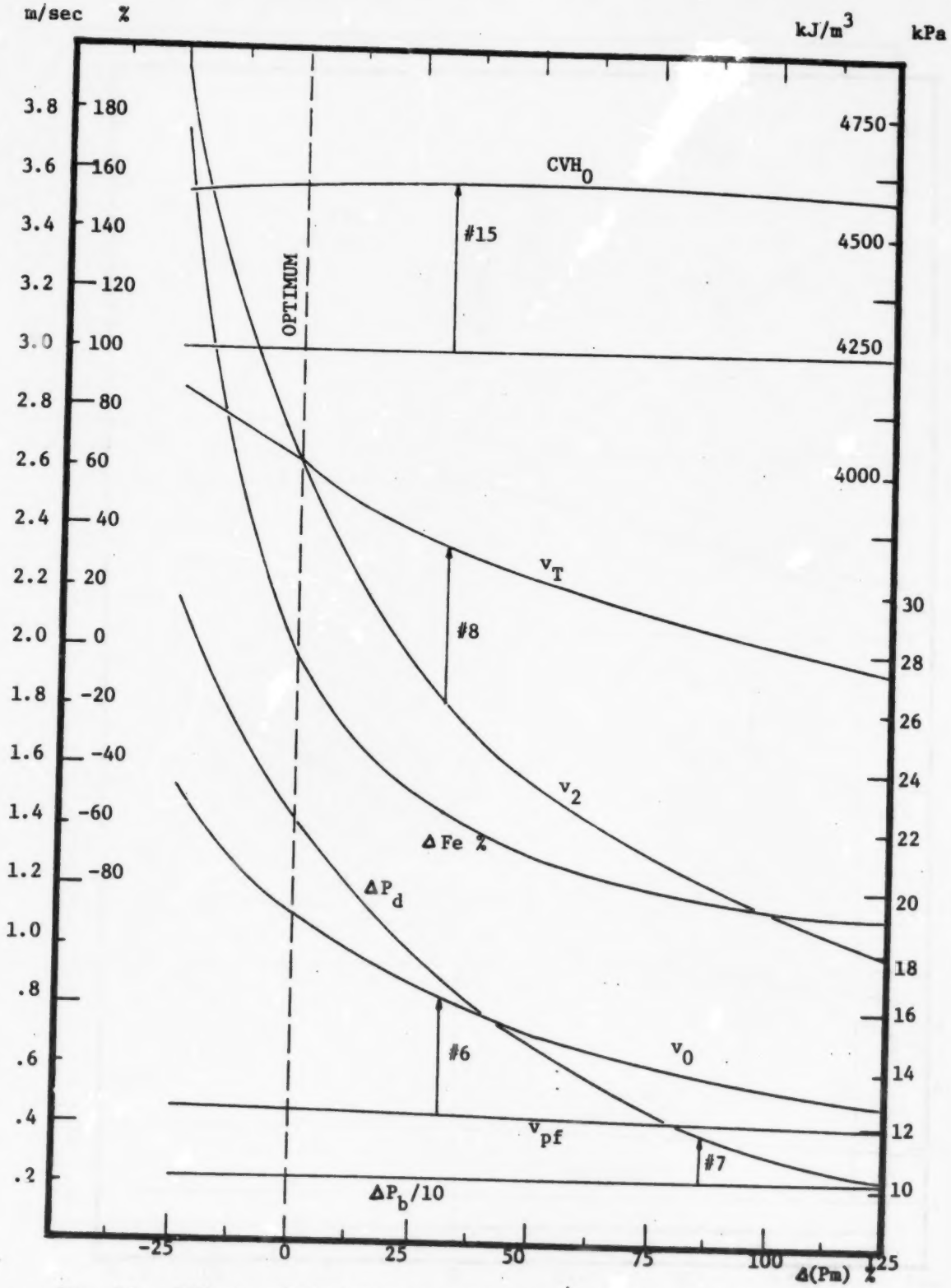

Fig. 15. Effects of variation in pressure in mixing vessel on the performance of the FBG. Case A.

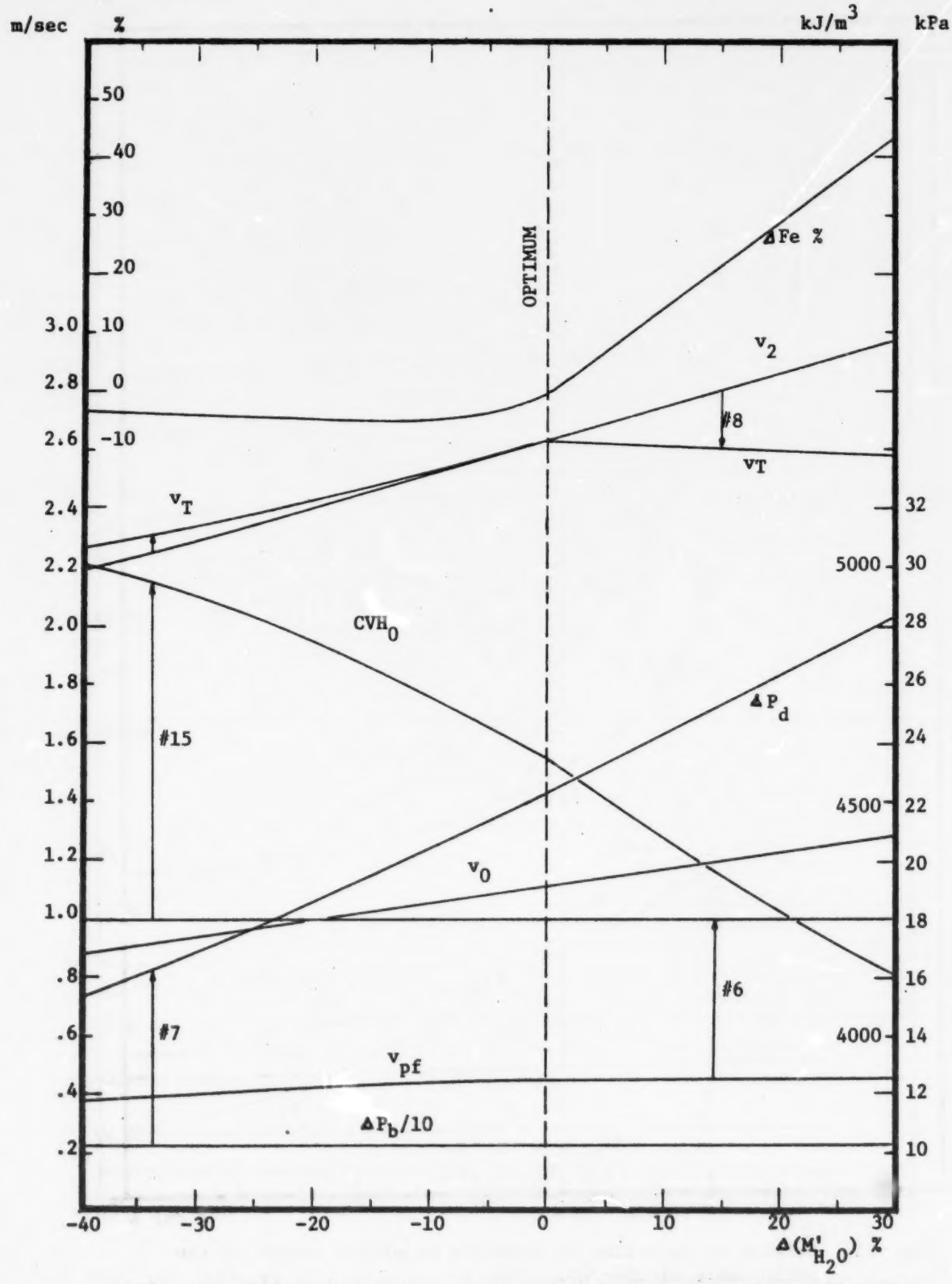

Fig. 16. Effects of variation in steam feed rate on the performance of the FBG. Case A.

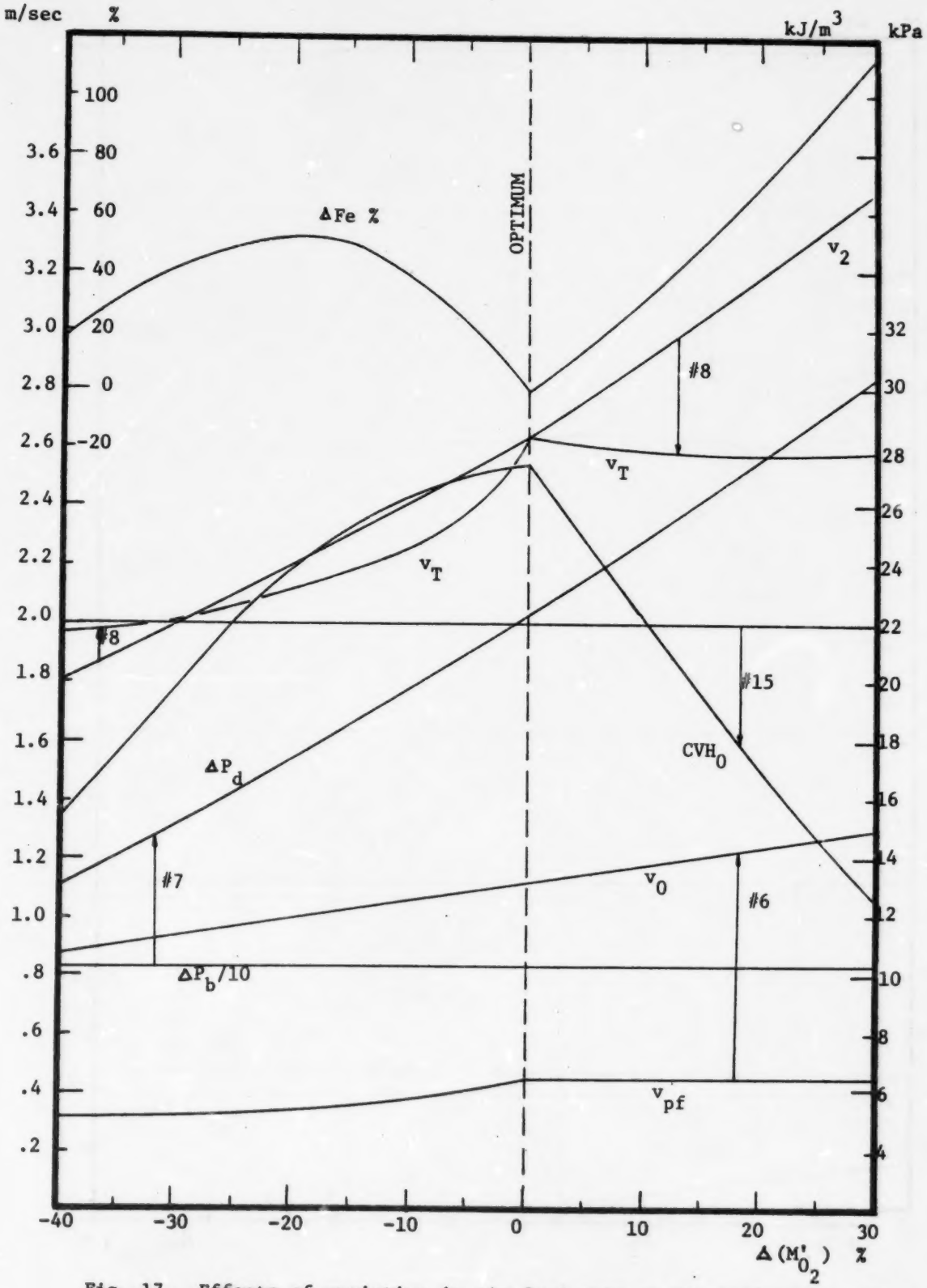

Fig. 17. Effects of variation in air feed rate on the performance of the FBG. Case A.

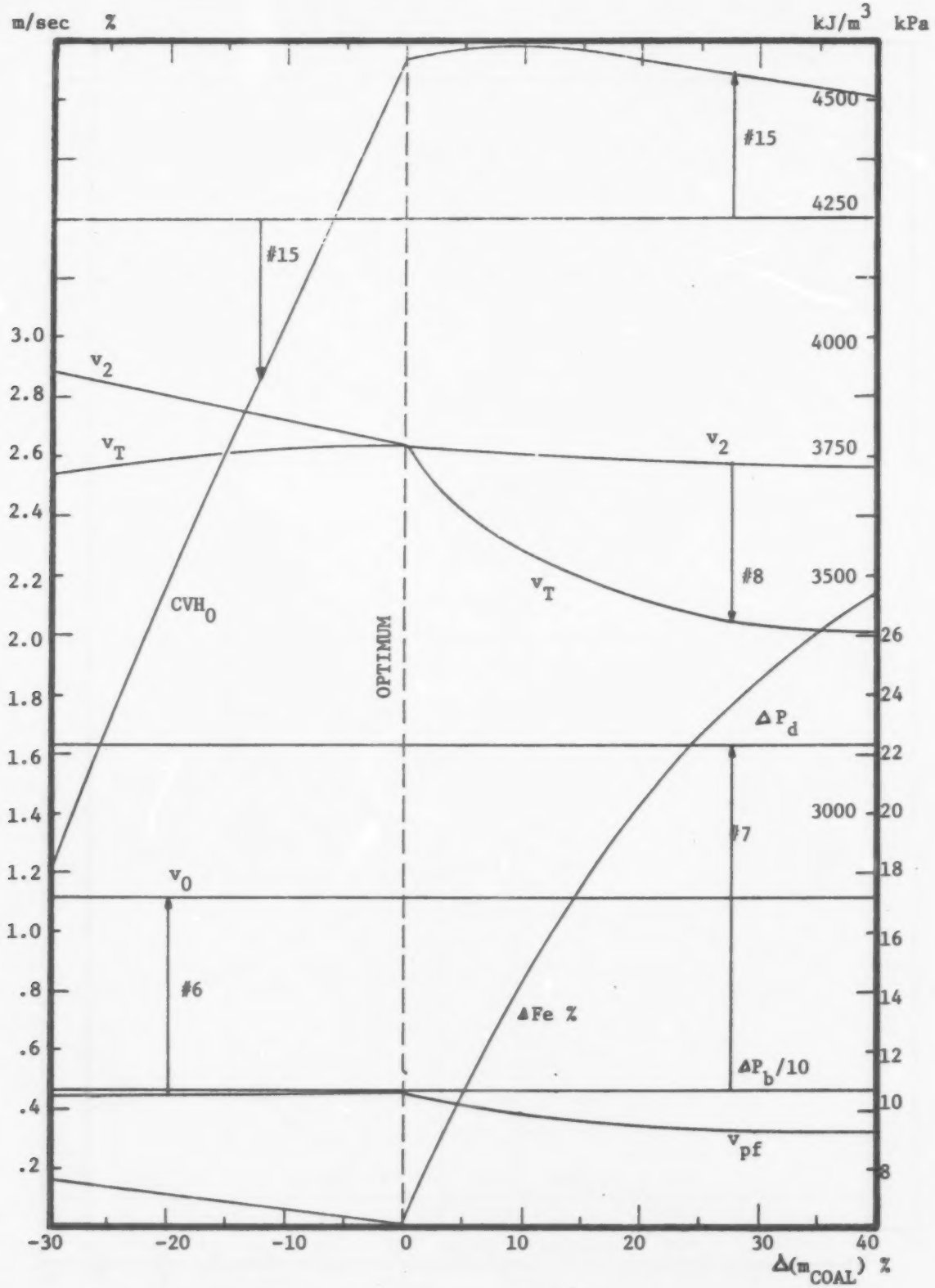

Fig. 18. Effects of variation in coal feed rate on the performance of the FBG. Case A.

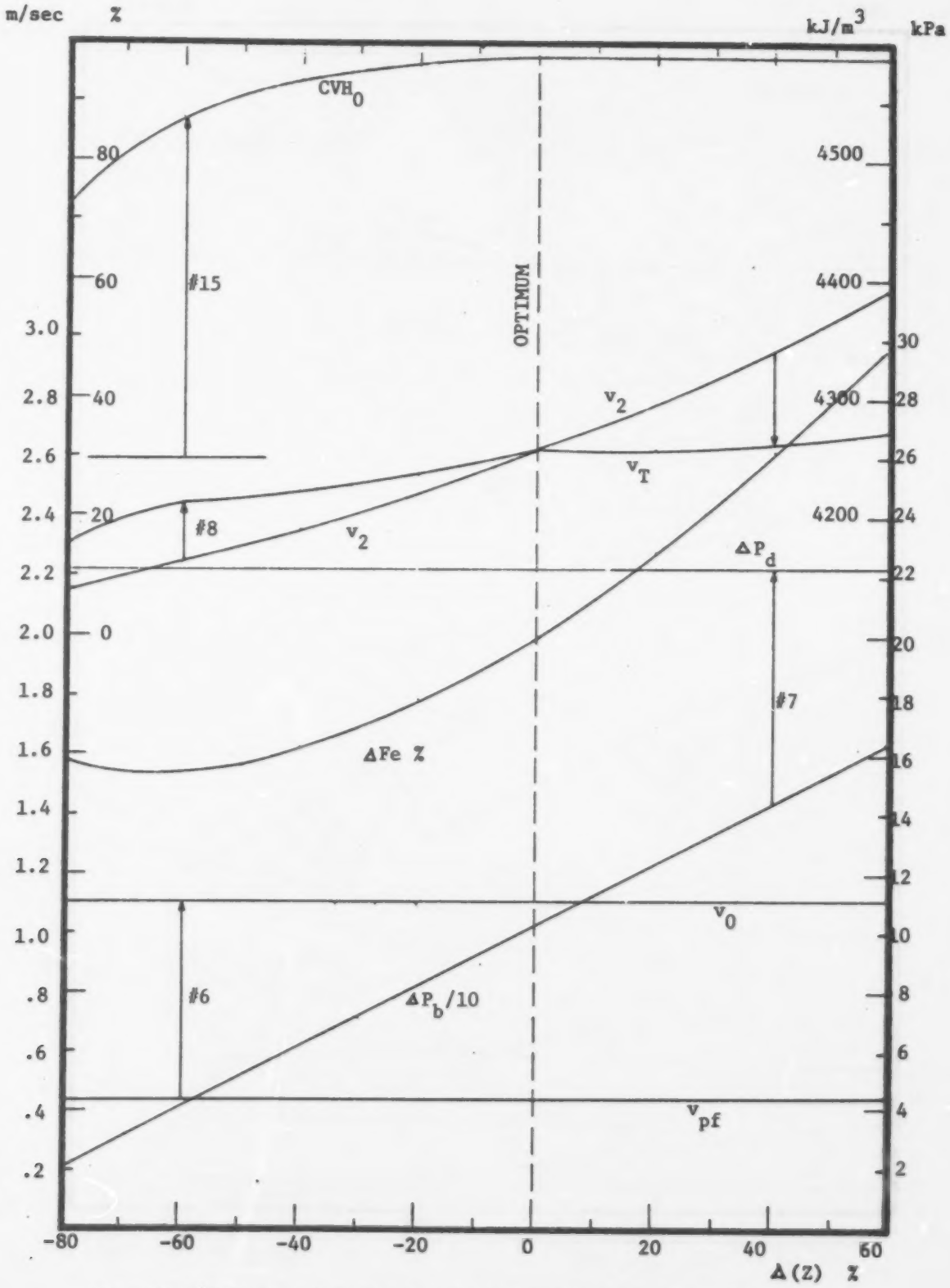

Fig. 19. Effects of variation in bed weight on the performance of the FBG. Case A.

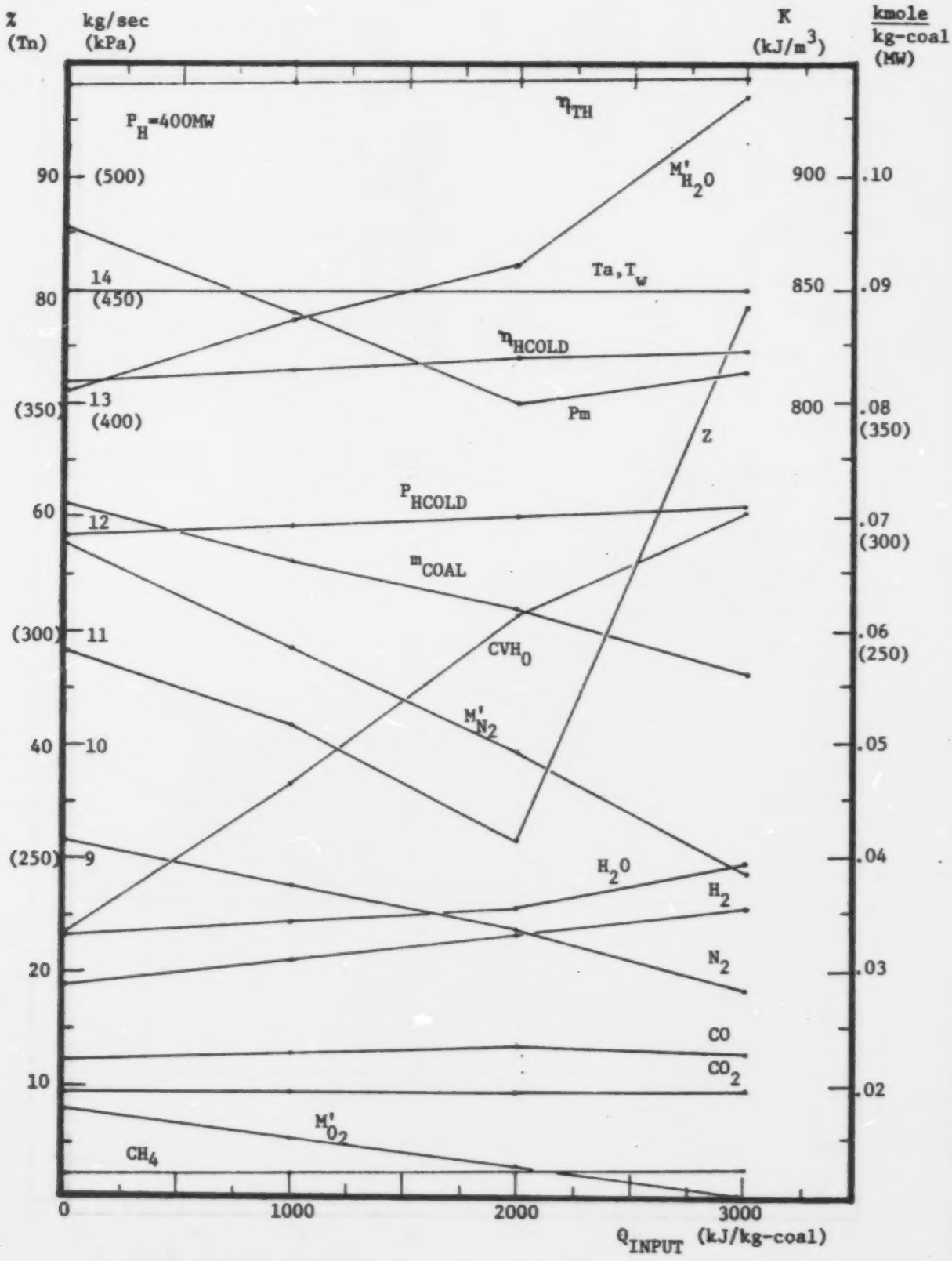

Fig. 20. Optimum performance. Case A. Effects of indirect heat input to FBG.

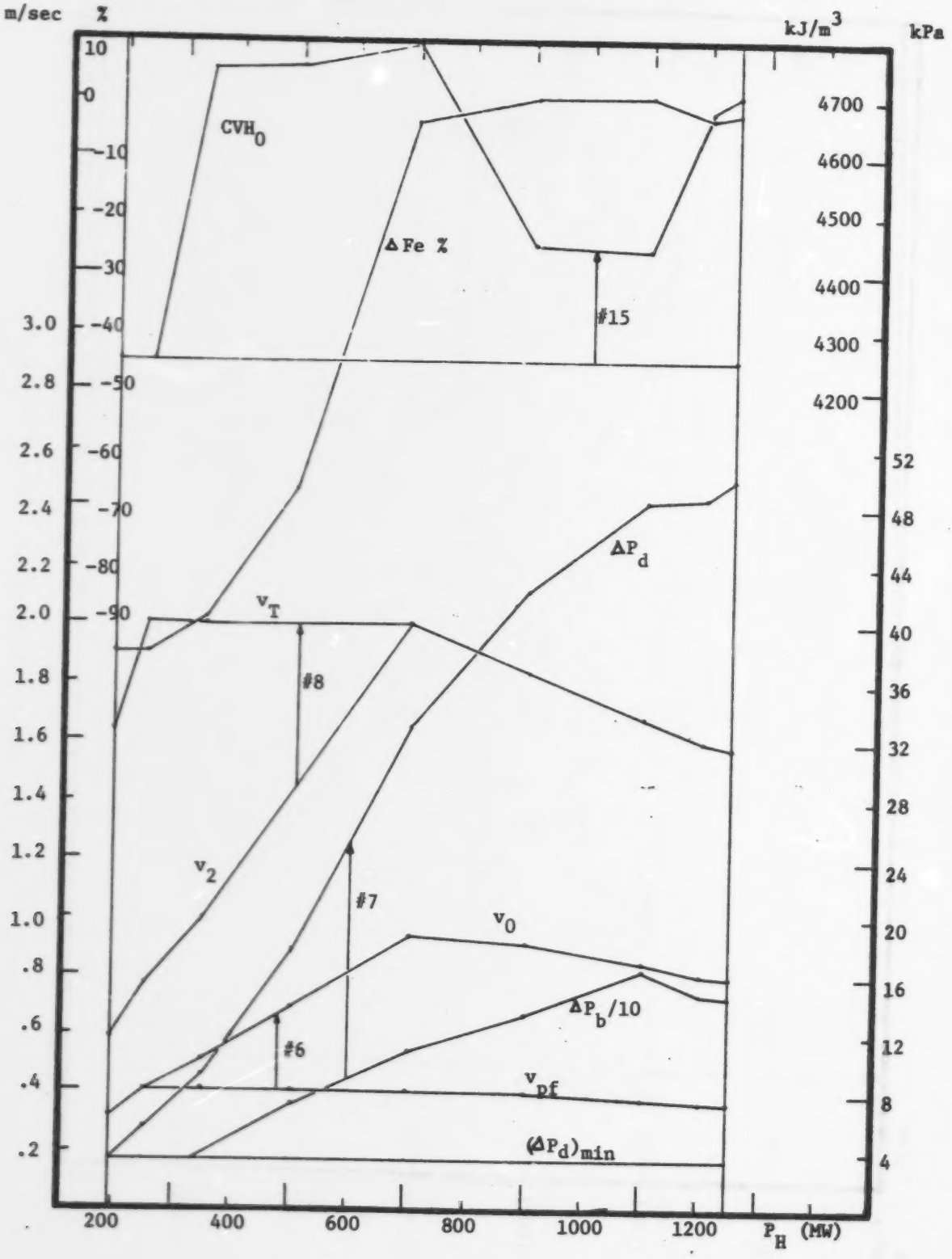

Fig. 21. Optimum performance. Case B.

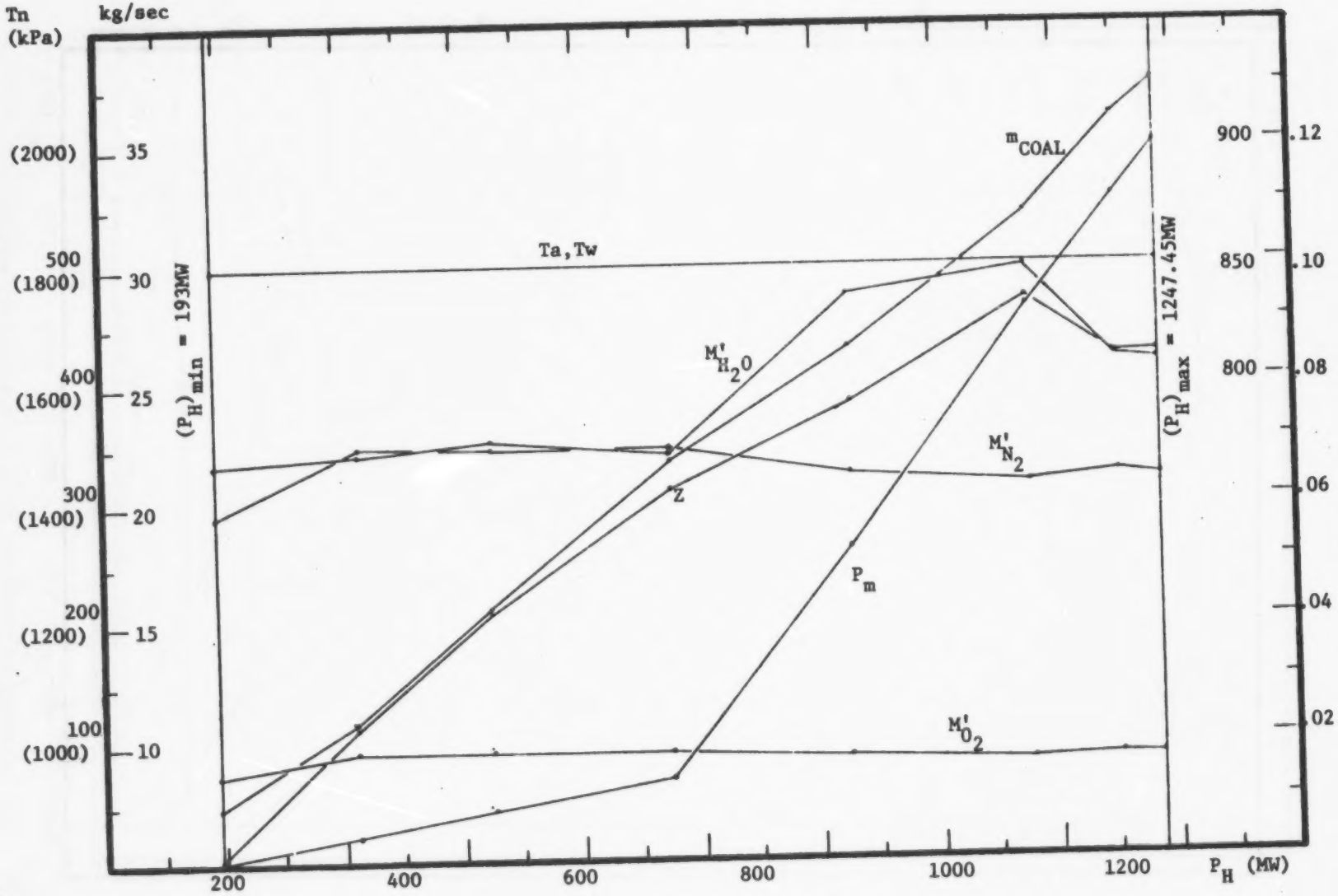

Fig. 22. Optimum performance. Case B.

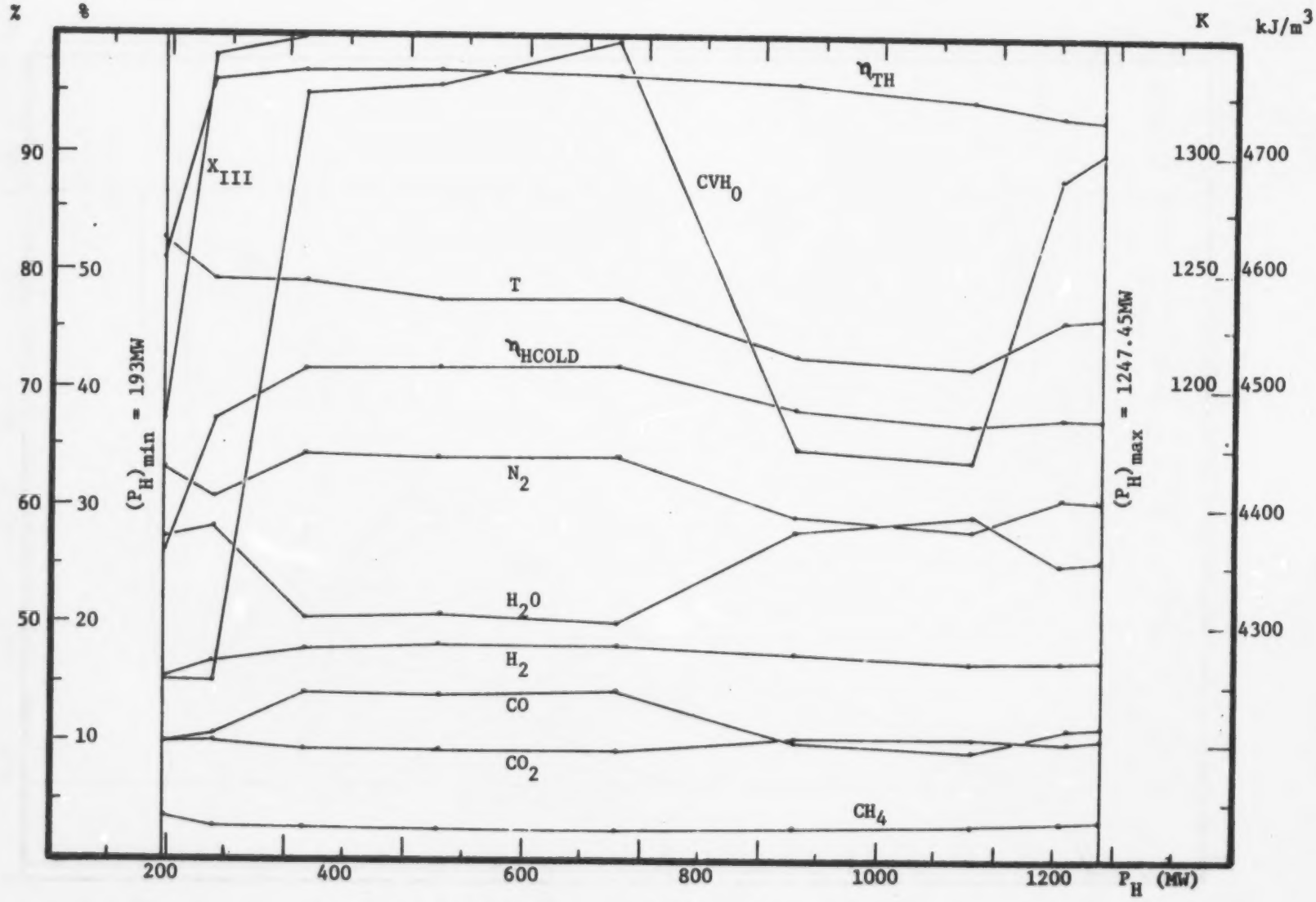

Fig. 23. Optimum performance. Case B.

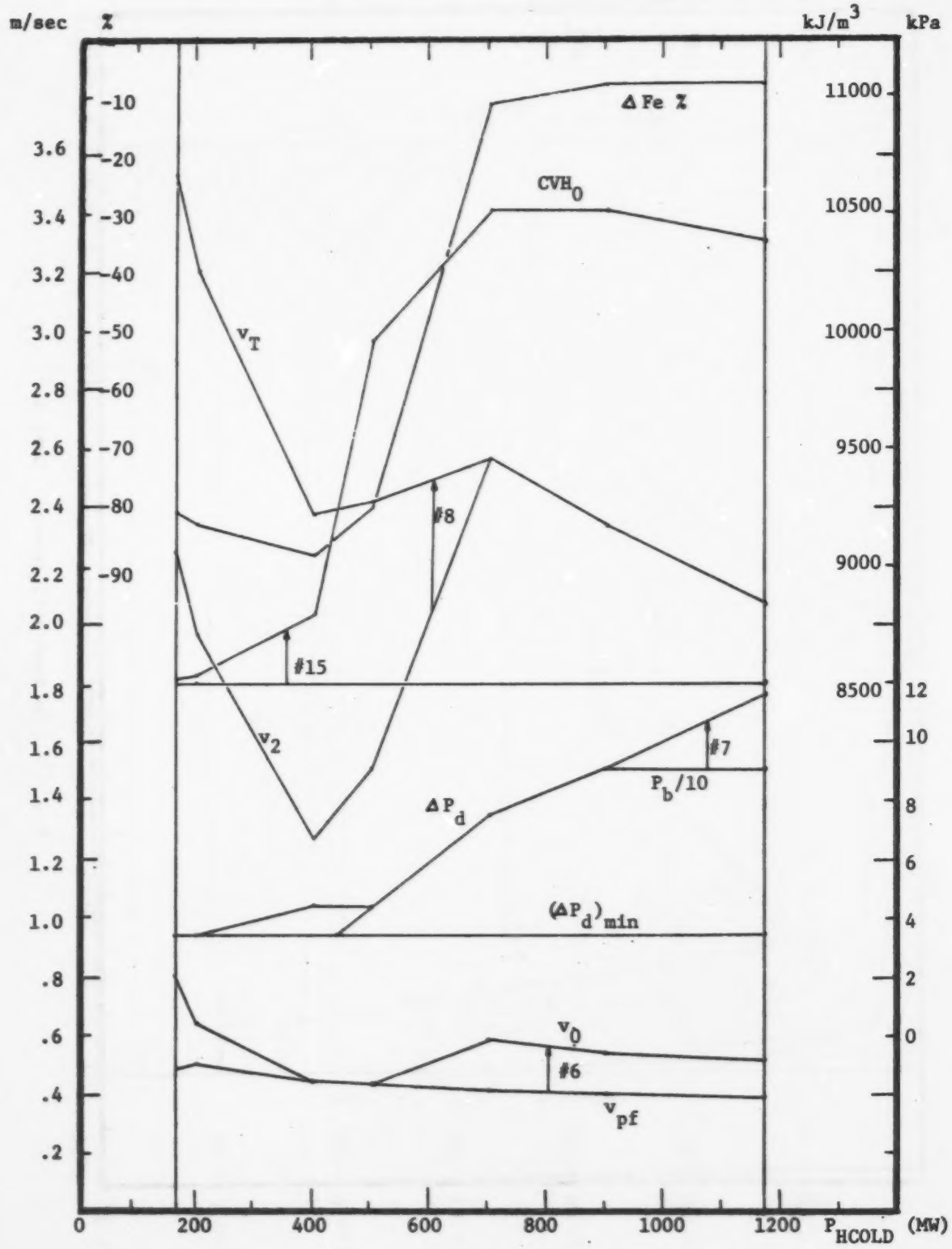

Fig. 24. Optimum performance. Case C (Steam + Oxygen).

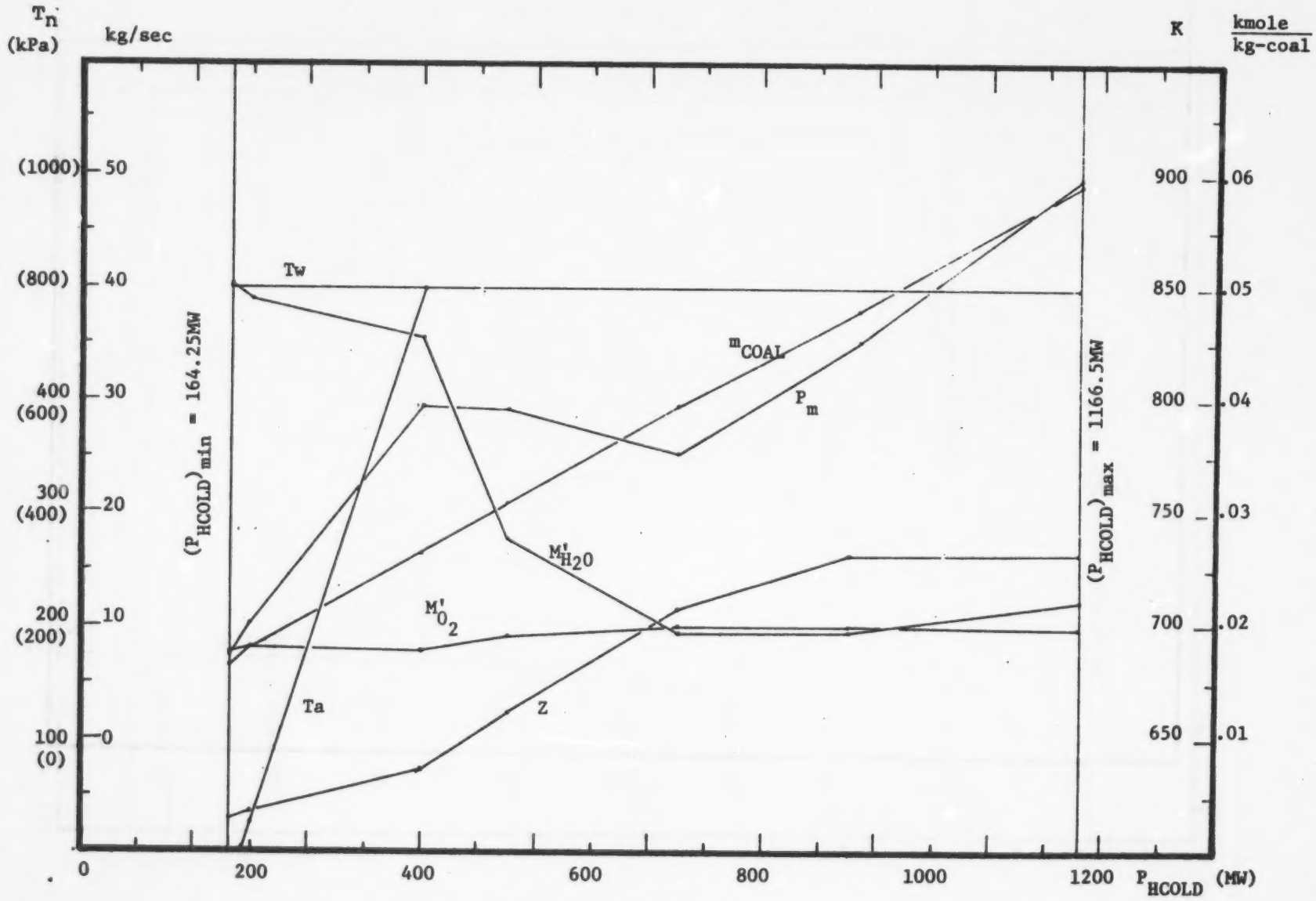

Fig. 25. Optimum performance. Case C (Steam + Oxygen).

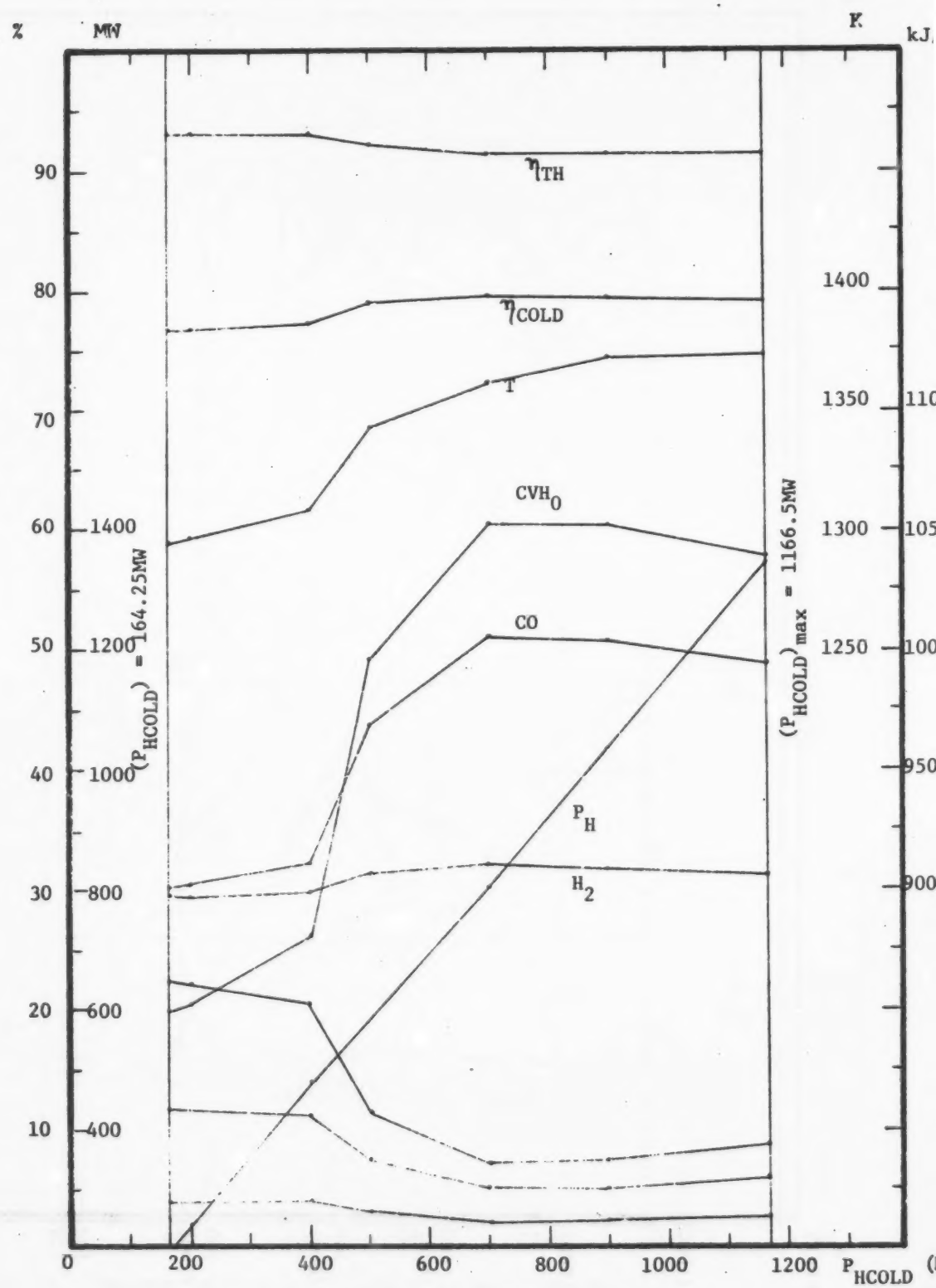

Fig. 26. Optimum performance. Case C (Oxygen + Steam).

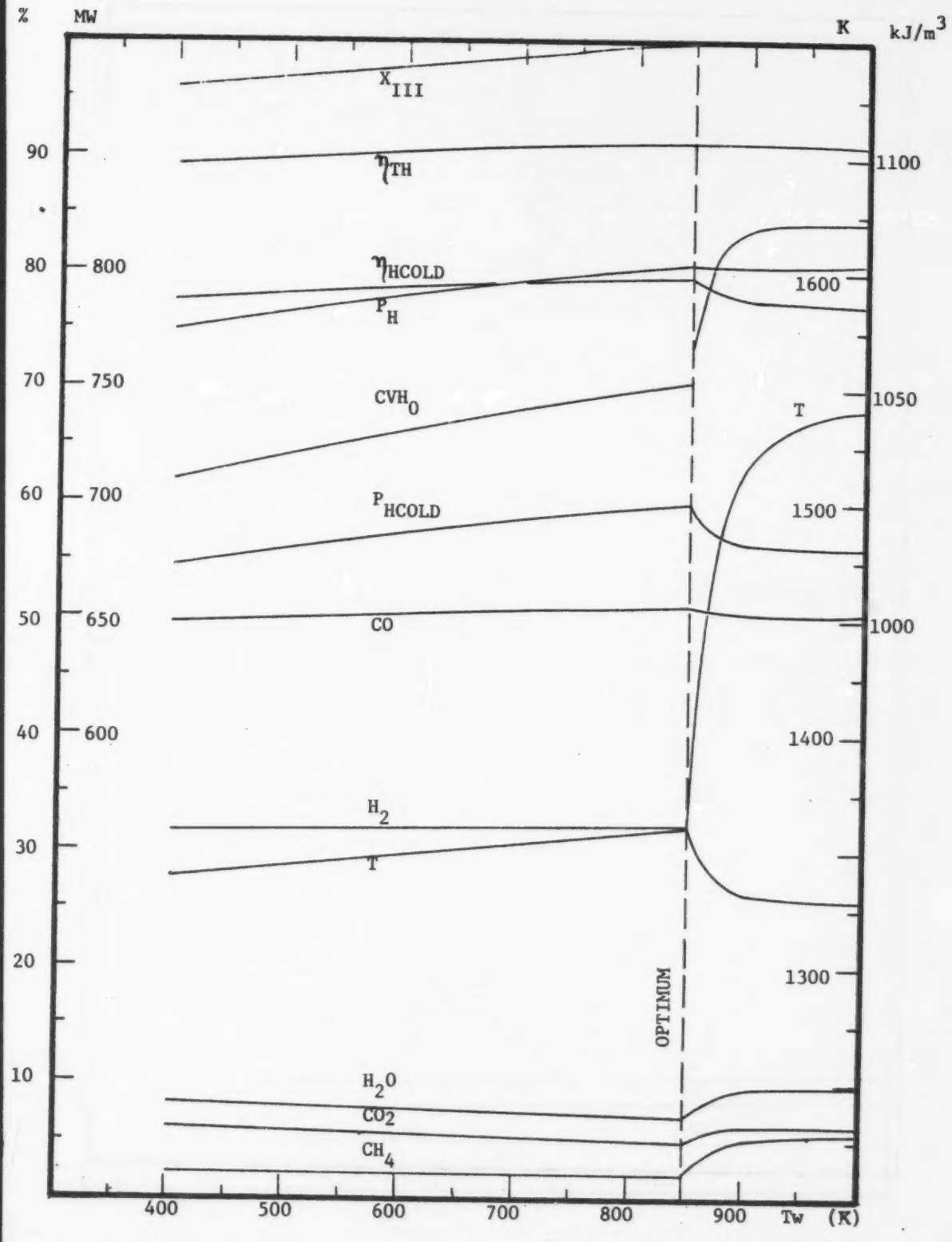

Fig. 27. Effects of variation in steam temperature on the performance of the FBG. Case C.

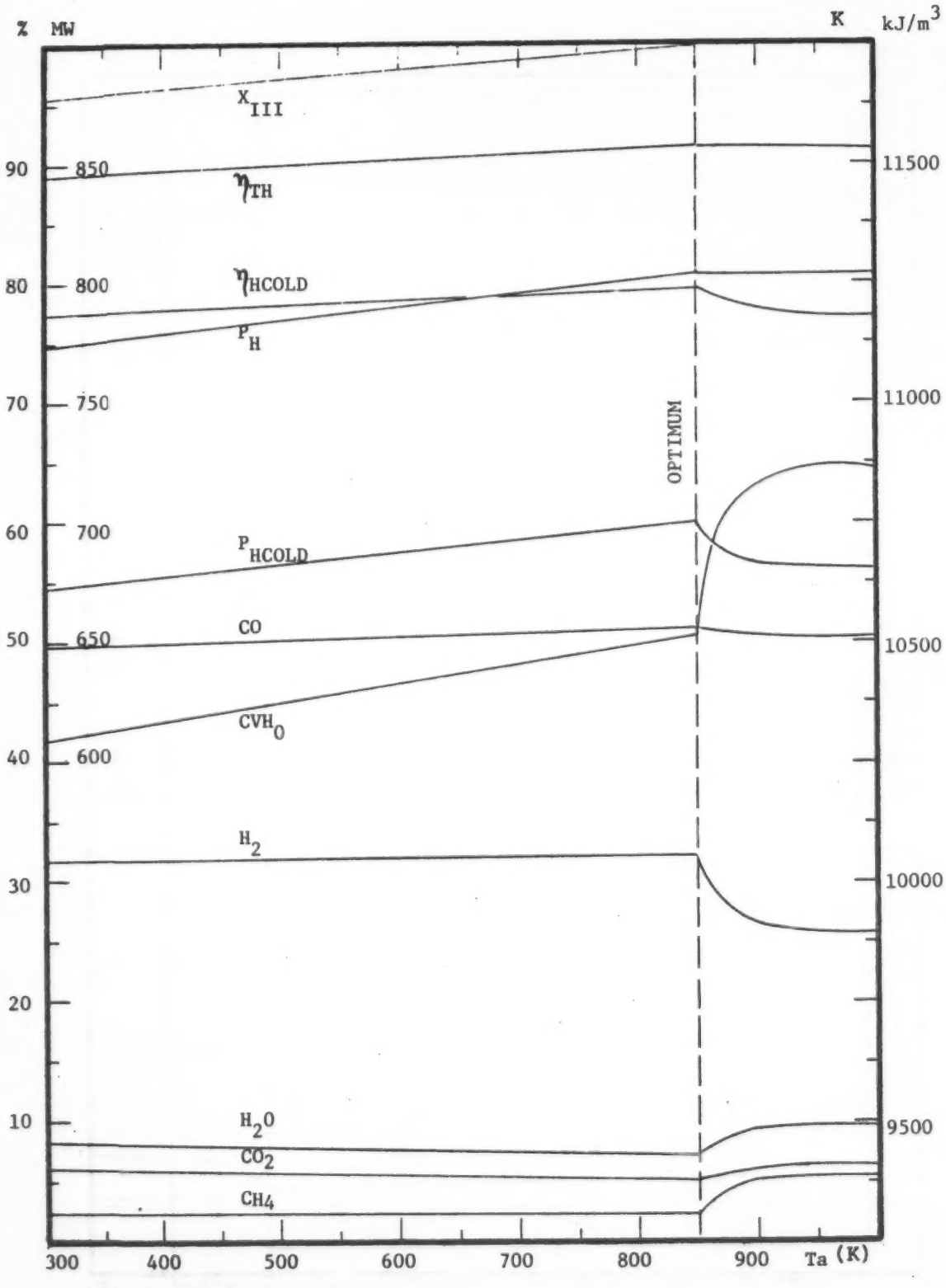

Fig. 28. Effects of variation in oxygen temperature on the performance of the FBG. Case C.

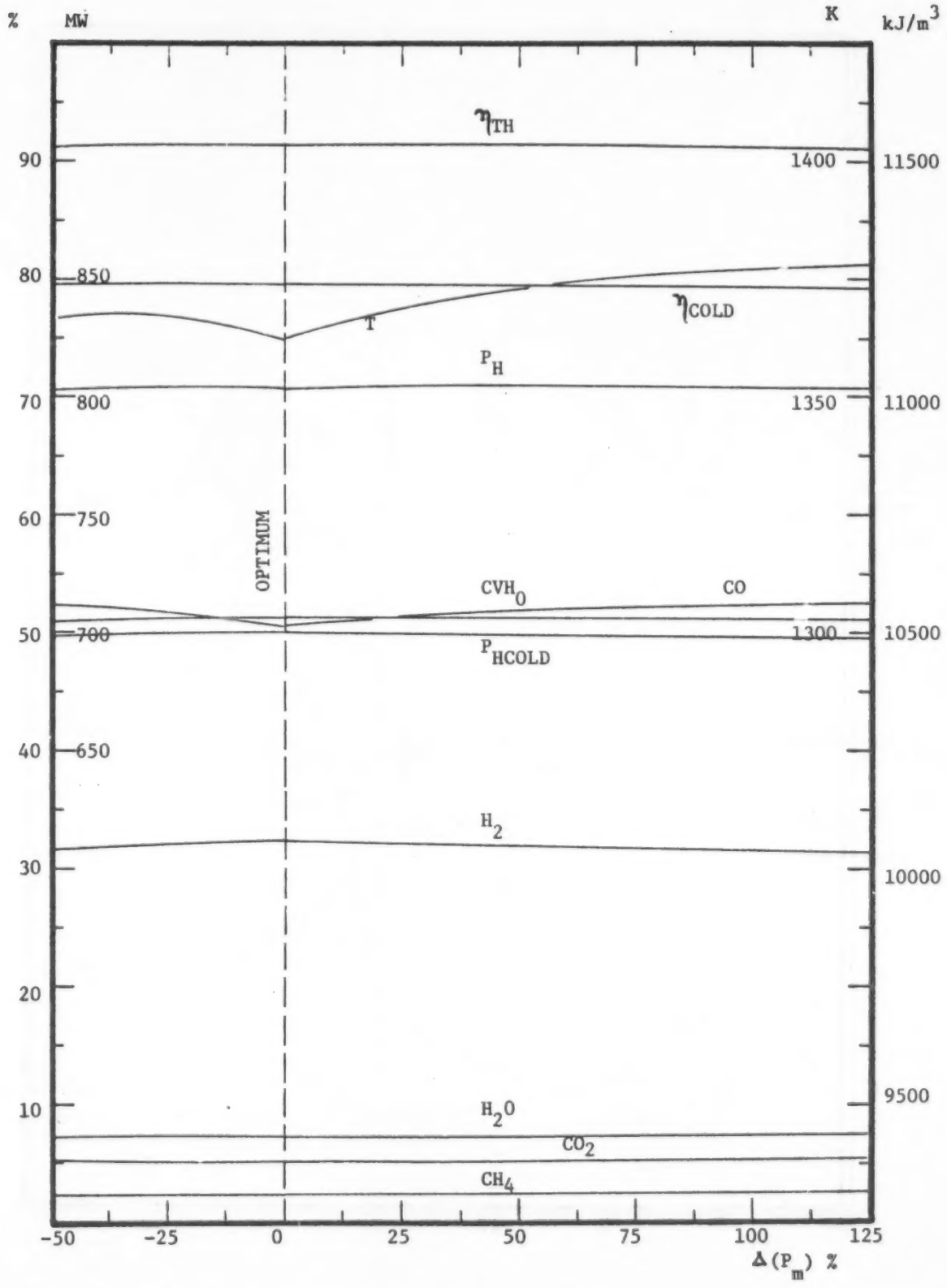

Fig. 29. Effects of variation in pressure in mixing vessels on the performance of the FBG. Case C.

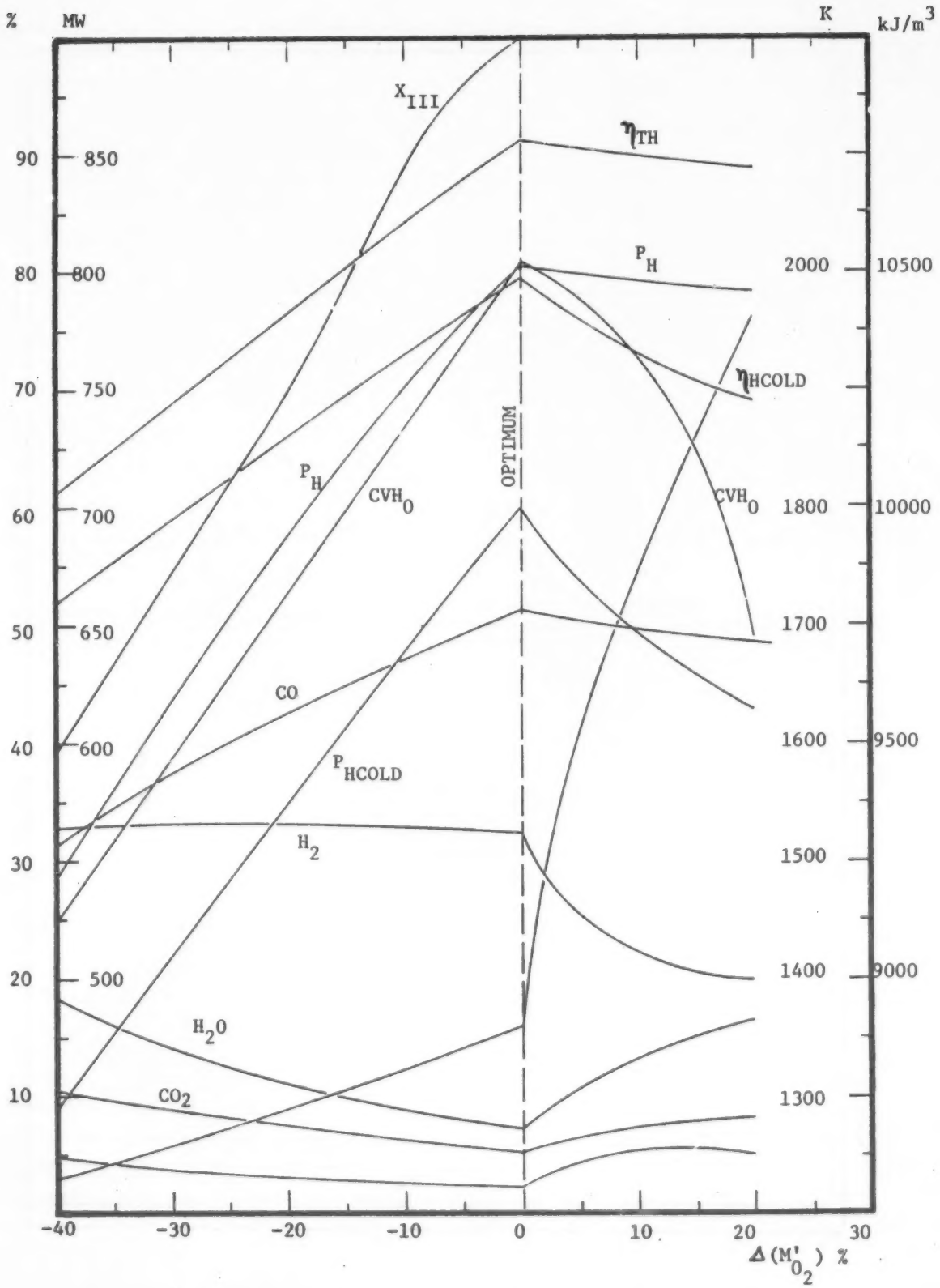

Fig. 30. Effects of variation in oxygen feed rate on the performance of the FBG. Case C.

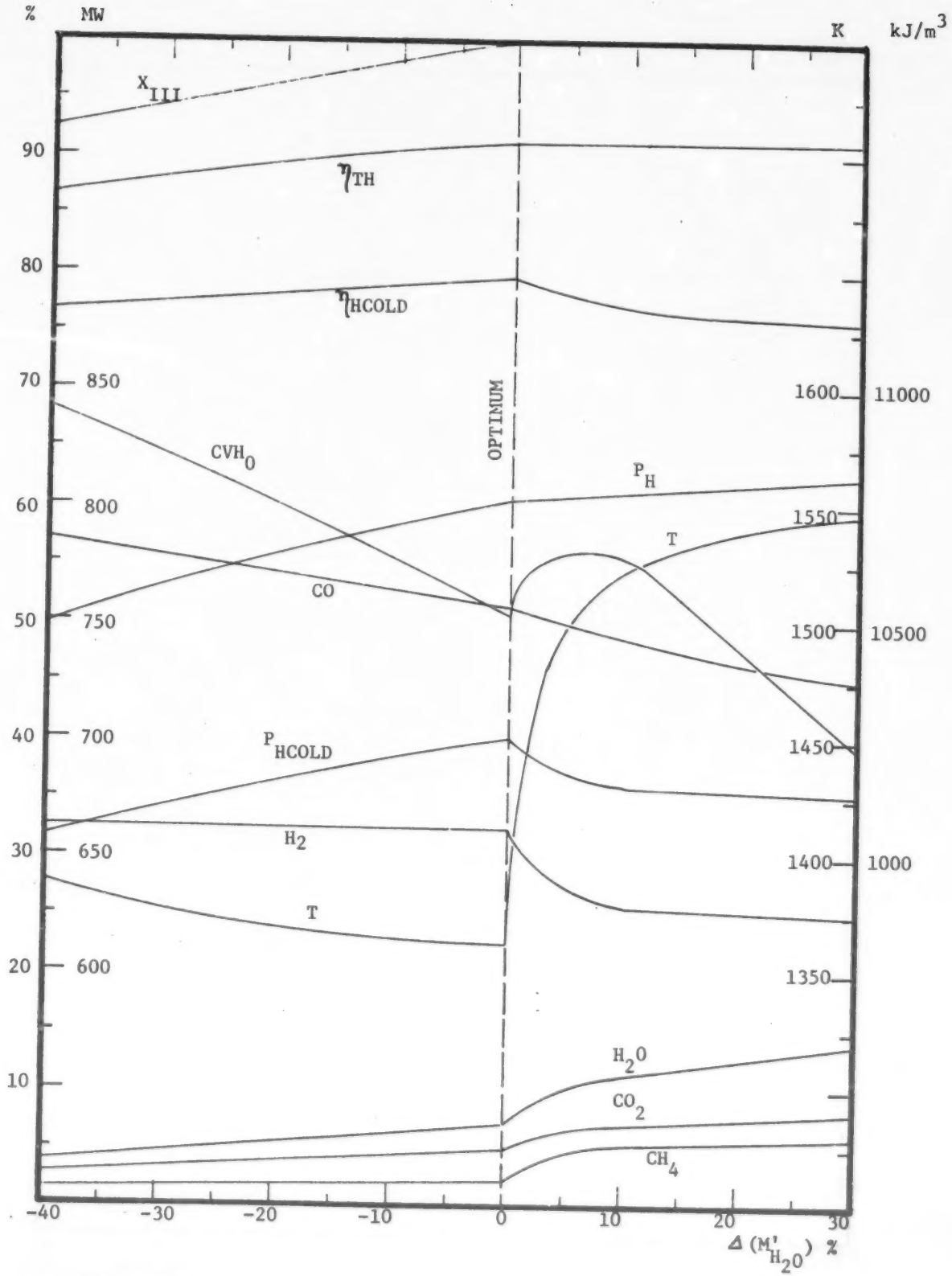

Fig. 31. Effects of variation in steam feed rate on the performance of the FBG. Case C.

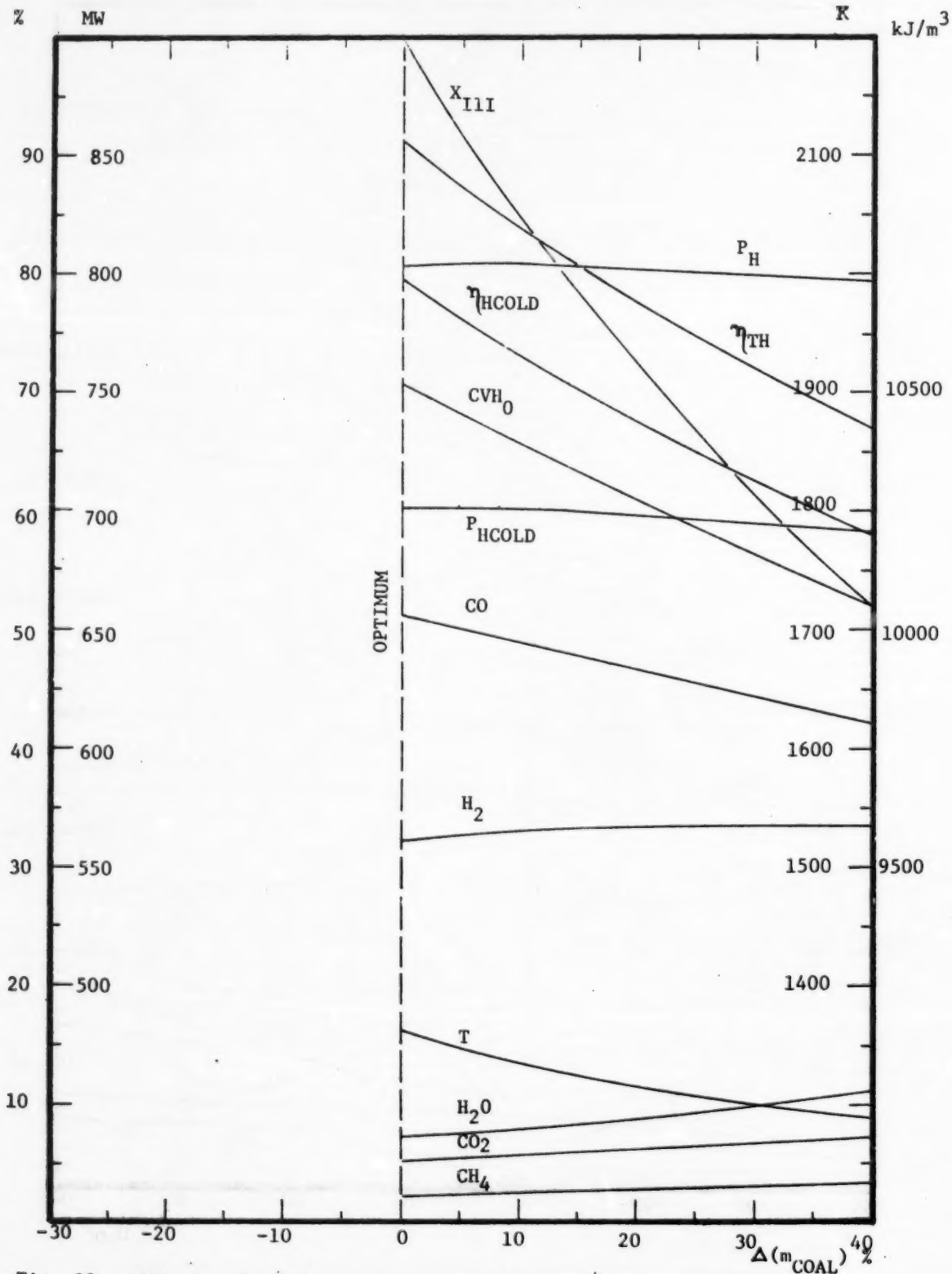

Fig. 32. Effects of variation in coal feed rate on the performance of the FBG. Case C.

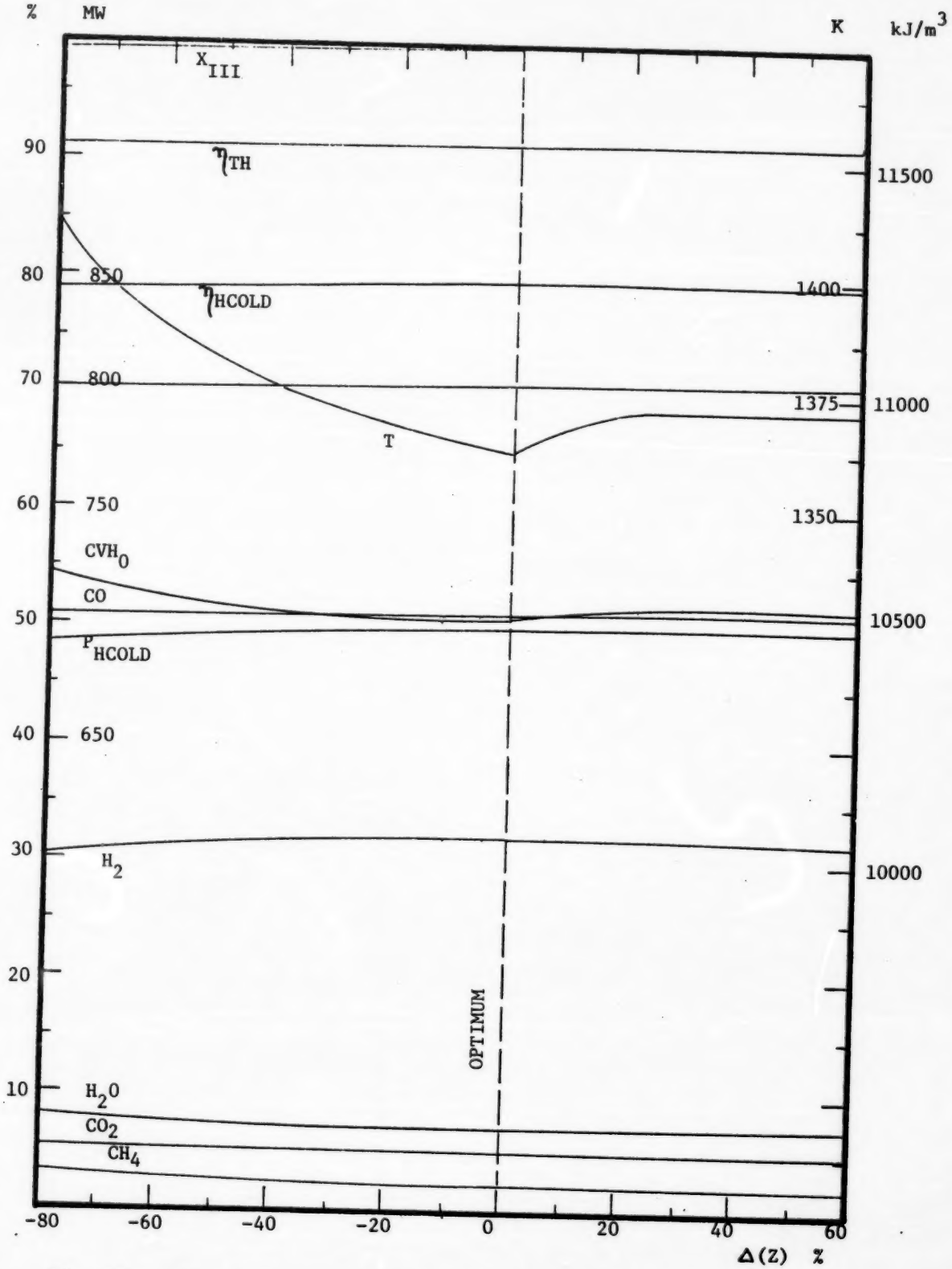

Fig. 33. Effects of variation in bed weight on the performance of the FBG. Case C.